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DOT/FAA/CT-88/31

FAA Technical Center
Atlantic City International Airport
N.J. 08405

AD-A208 191

Electromagnetic Emissions From a Modular Low Voltage Electro-Impulse De-Icing System

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March 1989

Final Report

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Technical Report Documentation Page

1. Report No. DOT/FAA/CT-88/31	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Electromagnetic Emissions from a Modular Low Voltage Electro-Impulse De-Icing (EIDI) System		5. Report Date March 1989
		6. Performing Organization Code
7. Author(s) Peter Zieve, Brent Huffer, James Ng		8. Performing Organization Report No.
9. Performing Organization Name and Address Electroimpact, Inc. 2721 NE Blakeley Street Seattle, WA 98105		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address Department of Transportation Federal Aviation Administration Technical Center Atlantic City International Airport, NJ 08405		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency Code ACD-230
15. Supplementary Notes COTR: Charles O. Masters Flight Safety Research Branch FAA Technical Center		

16. Abstract

An important consideration in the certification of Electro-Impulse De-icing (EIDI) systems for aircraft ice protection is electromagnetic interference (EMI). When the capacitor bank in an EIDI system discharges a large pulse of current travels down a transmission line to the coil. Subsequent radiation by the transmission line and the coil produces EMI. The Low Voltage Electro-Impulse De-icing system (LVEIDI) is unique in that the capacitor bank is mounted adjacent to the coil thereby eliminating most of the cables. Electromagnetic emissions from this system would then be primarily from the coil. The performed tests investigate the EMI environment inside and outside of both a composite and an aluminum wing. Due to the absence of the shielding effect of aluminum the problem of electromagnetic emissions is particularly severe when the wing is constructed of composite materials.

Measurements of the radiated electric field indicate that emissions from the aluminum wing were well within the standards. Some tests with the composite wing were within standards while others were not. It was found that the composite wing could be brought back into compliance through the addition of thin metallic shielding. Conducted emissions on the LVEIDI power feed cable were brought within standards with the addition of a line filter. An unshielded connection cable for a compass flux valve was run through the wing just behind the LVEIDI module. Discharge of the capacitor bank had no discernible effect on operation of the compass flux valve. No problems were observed in other tests of the wing internal environment.

17. Key Words Aircraft Icing Electromagnetic Compatibility Shielding Composite EIDI	18. Distribution Statement Document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	42	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

PREFACE

The electromagnetic interference (EMI) performance of special purpose devices and systems aboard aircraft has become of paramount importance in recent years, especially with the introduction of highly sensitive aircraft electronic components and navigational equipments. The radiation from Electro-Impulse De-icing (EIDI) systems and their potential effects on onboard equipment continues to be of interest to the Federal Aviation Administration (FAA) and other authorities. This evaluation of the electromagnetic emissions of a Low Voltage EIDI system was sponsored by the FAA Technical Center at Atlantic City International Airport, New Jersey. Mr. Charles O. Masters, the program manager of the FAA's Aircraft Icing Engineering and Development Program was instrumental in bringing to our attention the potential undesirable effects of electromagnetic radiations of EIDI and served as project engineer for this effort. His assistance was invaluable in the accomplishment of this project. Thanks also are extended to Dr. Glen Zumwalt of The Wichita State University for the loan of the composite wing section employed in these tests. Cy O'Young of the Boeing Commercial Airplane Company is thanked for his many helpful suggestions during this endeavor. Lastly, a special thanks is extended to Patrick Andre of the ELDEC Corporation for coming in on the weekend to conduct the EMI tests.

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LIST OF ABBREVIATIONS

DSO	Digital Storage Oscilloscope
E-FIELD	Electric Field
EIDI	Electro-Impulse De-icing
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
FAA	Federal Aviation Administration
H-FIELD	Magnetic Field
LVEIDI	Low Voltage Electro-impulse De-icing
RTCA	Radio Technical Commision for Aeronautics
SCR	Silicon controlled rectifier

EXECUTIVE SUMMARY

An important consideration in the certification of Electro-impulse De-Icing (EIDI) systems is electromagnetic interference (EMI) and electromagnetic compatibility (EMC). When the capacitor bank in an EIDI system discharges, a large pulse of current travels down a transmission line to the coil. The coil is one source of radiation. Another source is the cabling to the coil. In some proposed EIDI configurations transmission cables would run the length of the wing. The LVEIDI topology is unique in that for most installations the power supply is mounted adjacent to the coil thereby eliminating cables. Electromagnetic emissions from this system would then be predominantly from the coil.

The problem of electromagnetic emissions outside the wing is particularly severe when the wing is constructed of composite materials rather than aluminum. This is due to the absence of the shielding effect of aluminum. Even with the aluminum wing the question of the EMI/EMC environment inside of the wing must be addressed. The performed tests investigate the EMI/EMC environment inside and outside of both a composite and an aluminum wing.

Measurements of the radiated electric field indicated that emissions from the aluminum wing were well within the standards set by RTCA/DO-160B Section 21. Results of some of the tests with the composite wing were within standards while others were not. Standards were exceeded in the frequency band from 150 kHz to 30 MHz. In this band it was found that the radiated emissions could be brought back into compliance through the addition of thin metallic shielding.

Conducted emissions on the LVEIDI power feed cable were brought within RTCA/DO-160B Section 21 standards with the addition of an isolating line choke at the bus insertion point. The noise conducted up the power line was apparently due to the use of diodes in the LVEIDI doubler circuit.

No problems were observed in tests on the wing internal environment. A 2.2 volt signal was measured on an open circuit unshielded telephone wire run behind the de-icing module. The EMI signal was a voltage spike which occurred simultaneous with the discharge of the coil. A 2.2 volt spike would be adequate to create a transmission error on a digital transmission line. But this EMI signal was reduced to insignificant levels by either terminating the cable with 50 ohms or through the addition of shielding. An unshielded connection cable for a compass flux valve was run through the wing just behind the LVEIDI de-icing module. Discharge of the de-icing module had no discernible effect on operation of the compass flux valve.

INTRODUCTION

An important consideration in the certification of Electro-Impulse De-Icing (EIDI) systems is electromagnetic compatibility (EMC). When the capacitor bank discharges, a large pulse of current travels down a transmission line to the coil. The coil is one source of radiation. Another source is the cabling to the coil. In some proposed configurations of EIDI systems, cables would run the length of the wing [1,2,3]. The Low Voltage Electro-Impulse De-Icing (LVEIDI) topology is unique in that the power supply is mounted adjacent to the coil thereby in most cases eliminating cables [4]. Thus EMI/EMC emissions from this system should primarily be from the coil.

The EIDI fundamental frequency is in the audio band but considerable harmonics can be generated, particularly at the moment when the SCR (silicon controlled rectifier) is switched on. The current waveform at this moment is a sharp transition from a horizontal line to a ramp, a singularity rich in harmonics. RTCA/DO-160B Section 21 gives standards for radio frequency emissions. These standards limit the emissions in the RF frequencies to tenths of volts/m. Even more severe emission limitations might be imposed by military specifications.

The problem of electromagnetic emissions outside of the wing is particularly severe when the wing is constructed of composite materials rather than aluminum. This is due to the absence of the shielding effect of aluminum. Even with the aluminum wing the question of the EMI/EMC environment inside of the wing must be addressed. Navigational sense signals are conducted through the wing cavity. If EIDI operation should disturb these signals, undesirable effects on aircraft operation could possibly result. The performed tests explored the EMI/EMC environment inside and outside of both a composite and an aluminum wing.

DISCUSSION

TEST ARTICLE PREPARATION

Two wings were supplied for outfitting with LVEIDI modules. A 5-foot section of Cessna 210 wing was supplied by the FAA. The wing leading edge is comprised of .024" thick 2024 aluminum. The wing section is divided into four bays separated by ribs which are riveted in place. The nose has a radius of 1-1/4" with a gradual transition into the wing upper and lower surface. Due to the gentle transition the wing

can be deiced with a nose coil in each bay between ribs. Two nose coils were installed on tubular mounts as shown in Fig. 1. One coil deices a bay 13.75 inches wide and the second coil deices a 14.5 inch bay. The tubular mounts are fastened from rib to rib. Figure 2 shows one of the coils held up against the leading edge. A good match between the coil surface and the lead edge radius enhances the system efficiency. The 1-1/4" radius was achieved by baking the coil in the fixture shown in Fig. 3. The coil is wound, clamped into the fixture and then baked. After the bake cycle is completed the fixture is split yielding a perfectly dimensioned coil. The coil is mounted on the support tube as shown in Fig. 4. The coils have eighteen turns of .025x.194 inch copper ribbon. The oblong coil has outside dimensions of 2x3 inches.

The Cessna 210 has a leading edge spar 9 inches behind the nose. A separate LVEIDI power supply for each of the two coils is mounted on the forward surface of the leading edge spars resulting in transmission cables just several inches long. The power supplies have 1100 μF each and they both discharge at 450 volts. The discharge energy is therefore 111 Joules.

Initially electromechanical action on the Cessna 210 was less than desired due to the poor electrical characteristics of the .024" 2024 aluminum leading edge. This problem was resolved by riveting .030" copper doubler plates in front of the two coils. With this change the coils were capable of generating an extremely effective impulse. The weight of all components for one bay of ice protection on the Cessna 210 is shown in Table 1.

Table 1

COMPONENT WEIGHTS FOR ONE BAY OF ICE PROTECTION ON THE CESSNA 210 WING

coil and mount assembly	10.5 oz
capacitors	11.0 oz
SCR and diode pack	4.0 oz
capacitor mount	2.1 oz
bus bar	2.2 oz
control board	0.8 oz
SCR/diode clamp assembly	2.2 oz
doubler plate	1.5 oz
TOTAL	34.3 oz

A 38 inch section of a Learfan horizontal stabilizer was loaned to Elelectroimpact by The Wichita State University. This wing section is constructed of Kevlar, a composite which has very good energy

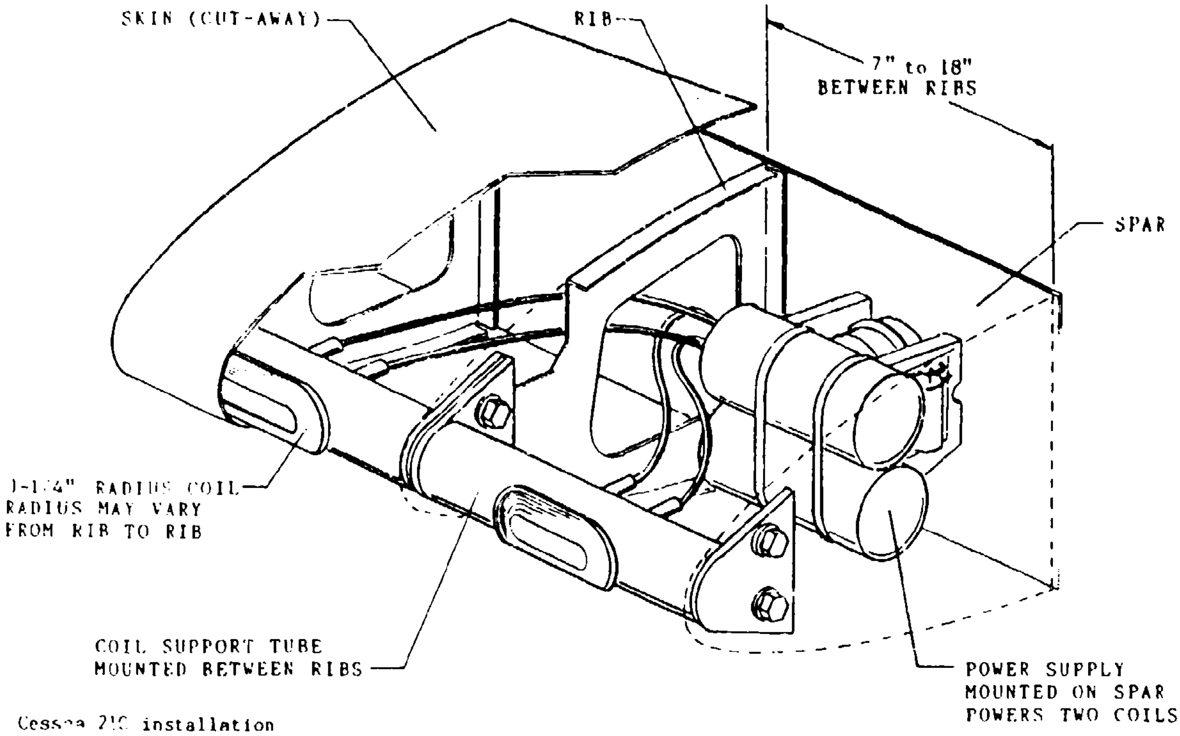


FIGURE 1 NOSE COILS INSTALLED IN THE ALUMINUM WING ON TUBULAR MOUNTS.

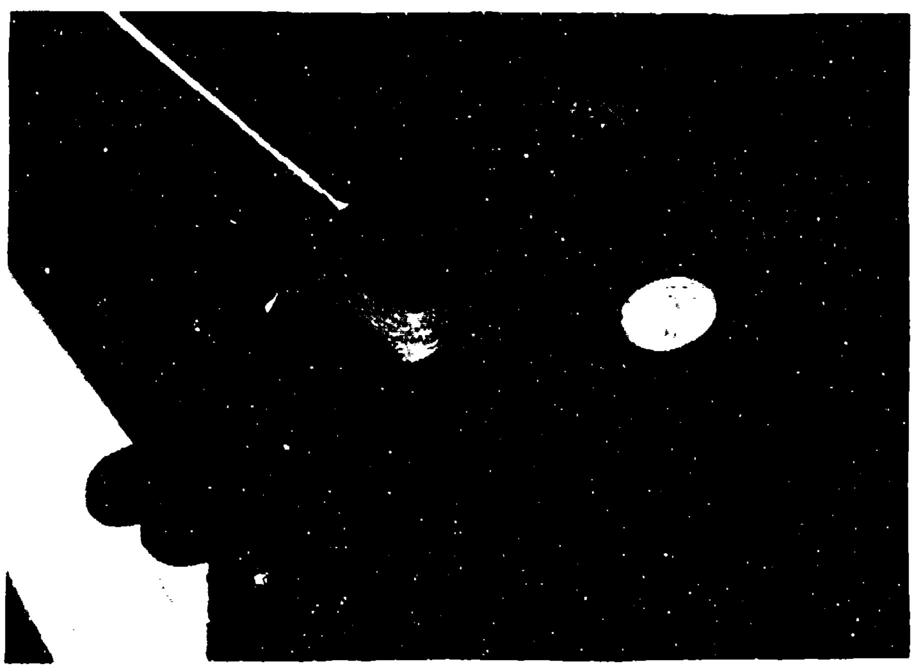


FIGURE 2 NOSE COILS HELD IN RELATION TO THE LEADING EDGE.

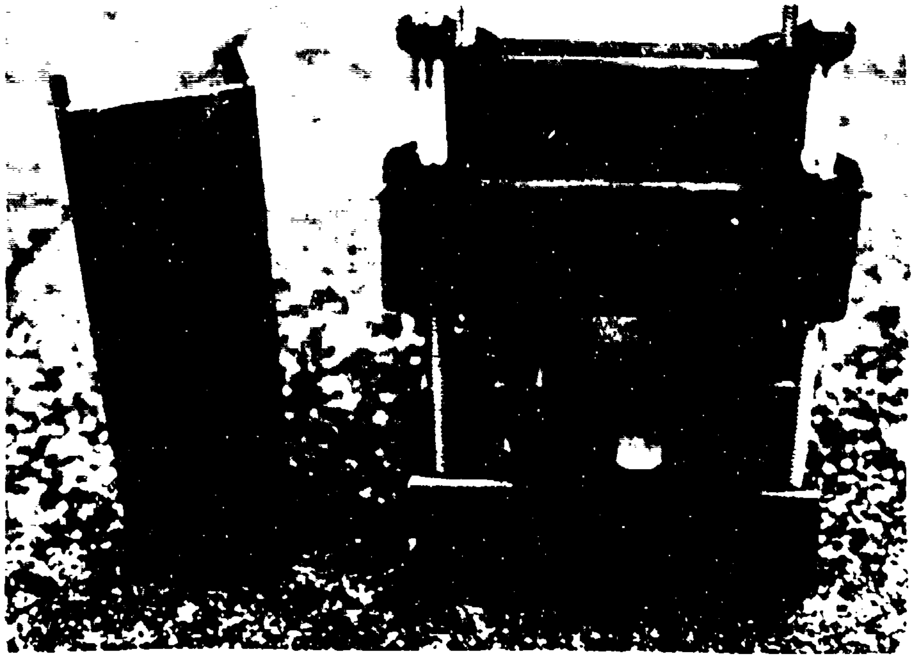


FIGURE 3   COIL BAKING FIXTURE EMPLOYED TO ACHIEVE PROPEP RADIUS.

FIGURE 4   COIL MOUNTED ON THE SUPPORT TUBE WHICH SPANS BETWEEN STIFFENERS.

absorption characteristics for bird strike survivability. This wing section features a small nose radius and nearly straight upper and lower surfaces just behind the nose. Upper and lower coils are indicated due to the extremely tight leading edge radius and abrupt transition. A nose mounted coil would not be effective at exciting both the upper and lower airfoil surfaces. The wing section came from The Wichita State University complete with upper and lower bonded doubler plates. The doubler plates are made of unalloyed .050 inch thick aluminum. Two sets of upper and lower LVEIDI coils were mounted from the leading edge spar, giving 19 spanwise inches to be cleaned by each coil pair. The mounting arrangement for one set is illustrated in Fig. 5. The coils are built to a 7 inch radius to accomodate the curvature of the doubler plates. The coils are wound with 27 turns of .025x.194 inch copper ribbon yielding a coil outside diameter of 2.25 inches.

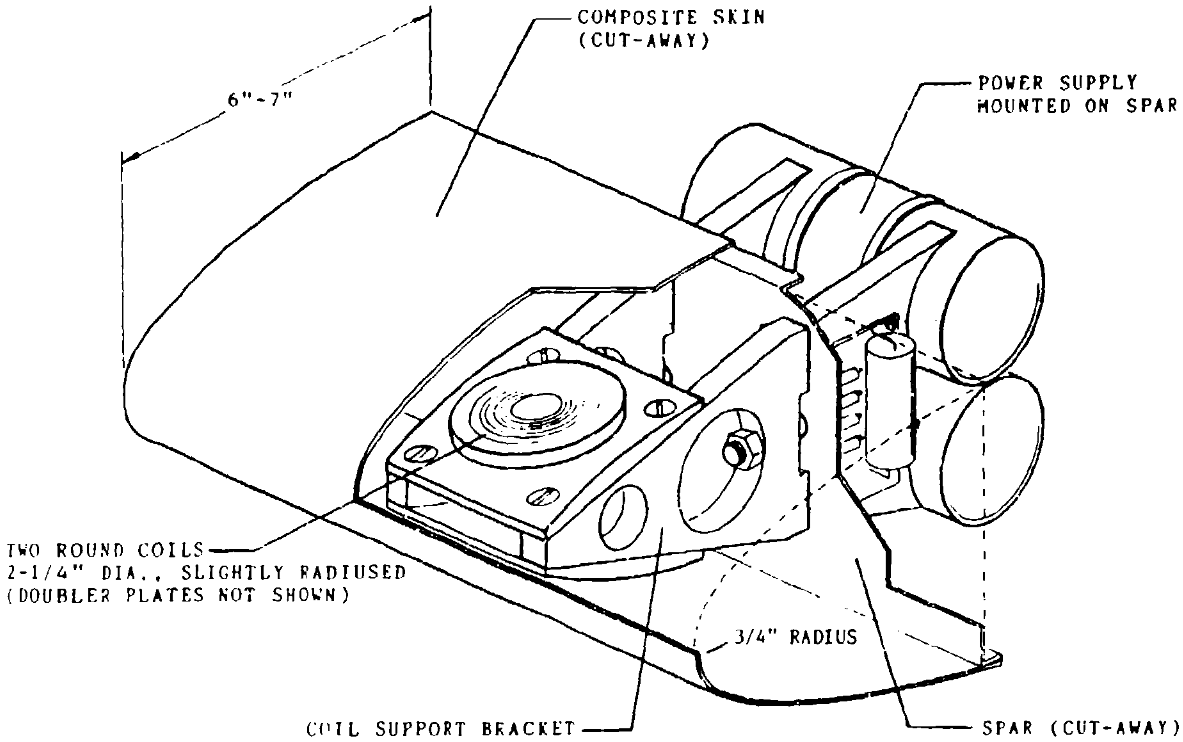
Figures 6 and 7 show two views of the coil pair assembly. Figure 6 shows the close conformance of the coils to the doubler plates. A slight spanwise taper to the wing results in the two coil mounts having different dimensions. Each pair of coils is wired in parallel to one LVEIDI power supply. The LVEIDI power supplies are mounted just aft of the spars resulting in transmission cables of several inches. The power supplies have 1100 µF each and they both discharge at 450 volts. The discharge energy is therefore 111 Joules. When operational the wing emits a loud thumping sound, quite distinctive from the sound emitted from the aluminum wing. The total system weight for the upper and lower coil pair and power supply system is detailed in Table 2.

Table 2

COMPONENT WEIGHTS FOR ONE BAY OF ICE PROTECTION ON THE LEARFAN COMPOSITE WING

2 coils and mount assembly	18.0 oz
capacitors	11.0 oz
SCR and diode pack	4.0 oz
capacitor mount	2.1 oz
bus bar	2.2 oz
control board	0.8 oz
SCR/diode clamp assembly	2.2 oz
doubler plate	1.1 oz
TOTAL	41.4 oz

The LVEIDI module may be powered by any frequency of conventional AC power [4]. In the Electroimpact lab the modules are run off of 60 Hz power and the discharge rate is about once every 30 seconds with the components in place. During the EMI emissions testing modules were energized with



Composite Lear Fan horizontal stabilizer installation

FIGURE 5 MOUNTING ARRANGEMENT FOR TOP AND BOTTOM COILS IN THE COMPOSITE WING.

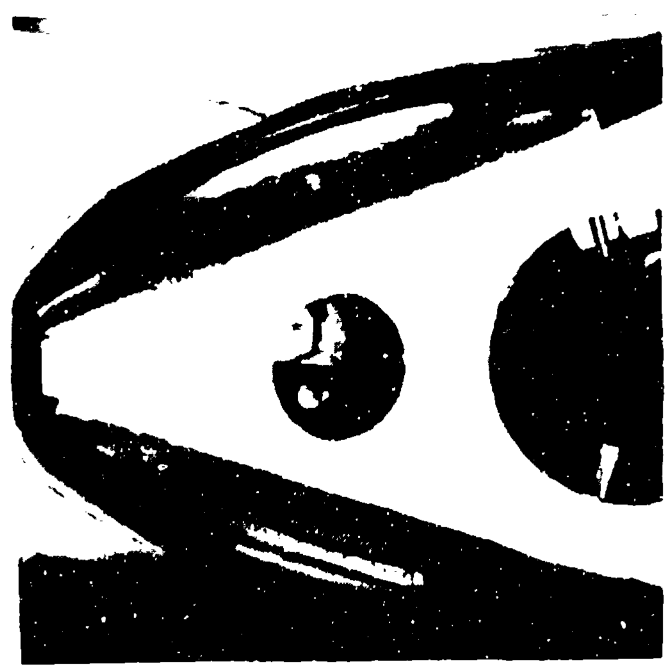


FIGURE 6 VIEW SHOWING CONFORMANCE OF TOP AND BOTTOM COILS TO DOUBLER PLATES.

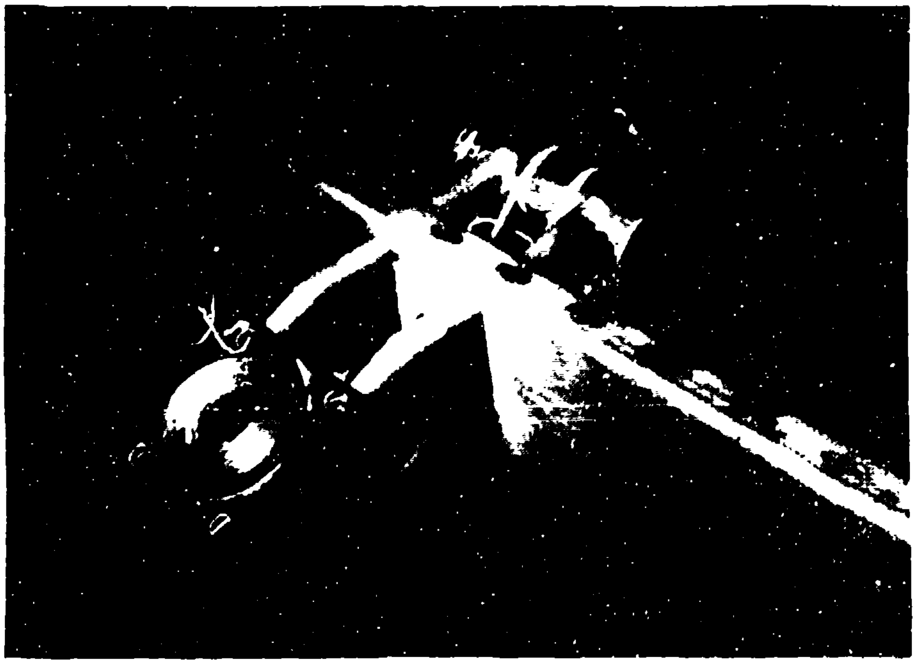


FIGURE 7   VIEW OF THE TOP AND BOTTOM COIL ASSEMBLY.

400 Hz power which results in a discharge rate of once every 4.5 seconds. This was convenient for testing since the increased discharge rate permitted a more rapid scan of the frequency spectrum.

TEST PLAN

The following is a summary of the tests proposed for this investigation of LVEIDI emissions.

1. Radiated E-Field measurements will be taken in accordance with Fig. 21-8 of RTCA/DO-160B [6]. The measurement antenna will be located on center with one of the two coils and one meter away. Measurement equipment will be in peak finding mode and adjusted for broadband since pulse discharge equipment is inherently broadband. A continuous scan of frequencies will be taken from 14 kHz to 1 gHz. Tests will be run with the wing in both a vertical and horizontal orientation. The RTCA gives standards for emmisions going up in frequency from 150 kHz.

2. Radiated H-Field measurements will be taken in accordance with Mil-Std 462, Section RE02 [7].

3. Conducted emissions on the LVEIDI power feed cable will be measured in accordance with RTCA/DO-160B Section 21.3. Broadband tests will be conducted for a continuous scan of frequencies from 14 kHz to 1 gHz.

Tests 4-8 are to be conducted in the Electroimpact Lab with the Cessna 210 wing:

4. A non-grounded unshielded transmission line will be run down the aircraft wing section approximately one foot aft of the LVEIDI modules. This line will traverse the length of the wing section. The outbound end will be open circuit and the root end will be connected to the input of a high speed digital sampling scope (100 MHz sampling rate). The scope will be set to capture the induced voltage on the line during the LVEIDI pulse and a plot will be made.

5. The above tests will be repeated with the transmission line terminated into 50 ohms.

6. The above tests will be repeated with the transmission line spaghetti wrapped in contact with the LVEIDI power feed cable and the transmission line first open circuit and then terminated with 50 ohms.

7. Tests 4,5 and 6 will be repeated substituting RG58/U shielded cable for the unshielded cable.

8. In the Electroimpact lab a compass flux valve will be installed in the external tip of the aircraft wing section. The connection cable for the compass will be passed one foot behind the LVEIDI modules. The voltages induced into the interconnect cable during the LVEIDI pulse will be recorded with the high speed digital sampling scope. The effect of the LVEIDI power pulse on compass operation will be documented.

Tests 1-3 are to be performed with both the aluminum and the composite wing in the EMI test facility of the Eldec Corp., Lynnwood, WA.

RESULTS

EMI TEST CHAMBER RESULTS

The emissions scans recorded at Eldec are contained in Appendix A. The EMI room instrumentation scans the frequency bands and spikes are recorded at the moment the module discharges.

On the measurement for broadband electric field radiation three antennas were required to scan the frequency band. The RTCA DO/160B Fig. 21-7 gives standards for emissions from 150 kHz to 1.215 GHz. The first antenna scans from 14 kHz to 30 MHz. The second antenna gives coverage from 30 MHz to 200 MHz. The third yields the response from 200 MHz to 1.2 GHz. Therefore the entire scan is shown on three consecutive scans.

The Eldec test results contained in Appendix A are summarized in Tables 3 to 6.

TABLE 3

TESTS ON RADIATED E-FIELD MEASUREMENT- ALUMINUM WING

Appendix Fig. No.	Description	Results
A-1	14 kHz to 30 MHz, vertical orientation	within standards
A-2	30 MHz to 200 MHz, vertical orientation	within standards
A-3	200 MHz to 1 GHz, vertical orientation	within standards

A-4	14 kHz to 30 MHz, horizontal orientation,	within standards
A-5	30 MHz to 200 MHz, horizontal orientation	within standards
A-6	200 MHz to 1 GHz, horizontal orientation	within standards

TABLE 4

TESTS ON RADIATED E-FIELD MEASUREMENT- COMPOSITE WING

Appendix Fig. No.	Description	Results
A-7	190 kHz to 30 MHz, vertical orientation	emissions exceed standards
A-8	190 kHz to 30 MHz, vertical orientation, shield power supplies	emissions exceed standards
A-9	150 kHz to 30 MHz, vertical orientation, shield power supplies and broaden doubler plates with copper sheets	emissions exceed standards
A-10	150 kHz to 30 MHz, vertical orientation, shield power supplies, broaden doubler plates with copper sheets, cover wing with .0013 aluminum foil	emissions exceed standards
A-11	150 kHz to 30 MHz, vertical orientation, shield power supplies, broaden doubler plates with copper sheets, wrap aluminum foil around wing	within standards
A-12	150 kHz to 30 MHz, vertical orientation, shield power supplies, remove broadened doubler plates, wrap aluminum foil around wing	one spike above the standards line at about 15 MHz

A-13	same as above with .001" aluminum foil inside of the wing.	one spike above the standards line at about 15 MHz
A-14	30 MHz to 200 MHz, vertical orientation	within standards
A-15	200 MHz to 1 GHz, vertical orientation	within standards
A-16	14 kHz to 30 MHz, horizontal orientation	emissions exceed standards
A-17	30 MHz to 200 MHz, horizontal orientation	within standards
A-18	200 MHz to 1 GHz, horizontal orientation	within standards

TABLE 5

TESTS ON CONDUCTED INTERFERENCE- HORIZONTAL COMPOSITE WING

Appendix Fig. No.	Description	Results
A-19	150 kHz to 30 MHz, no input filter	emissions exceed standards up to 600 kHz
A-20	150 kHz to 30 MHz, with input filter	within standards
A-21	150 kHz to 30 MHz, with input filter	within standards

TABLE 6

MAGNETIC FIELD TESTS (STANDARDS NOT APPLICABLE)

Appendix Fig. No.	Description
A-22	10 kHz to 30 MHz, aluminum wing vertical
A-23	10 kHz to 30 MHz, aluminum wing horizontal
A-24	10 kHz to 30 MHz, composite wing vertical

No emissions in excess of standards were observed for Radiated E-Field measurements (Figs. A-1 to A-6) with the aluminum wing. This can be attributed to the shielding influence of the aluminum in comparison with tests performed on the composite wing.

The first conducted interference test (Fig. A-19) exhibited excessive low frequency emissions. Note that the noise is falling off at a rate of about 20 dB/octave, typical of a step singularity. This may be attributed to the use of rectifying diodes in the LVEIDI power supply [4]. The following two tests showed that a simple filter is effective at shielding the noise from the power line. A power line filter should not be a major problem for LVEIDI since in the configurations proposed all modules would be wired in parallel, back to a switch which taps power from the bus. The switch would provide a convenient location for a single insertion filter which would isolate all of the LVEIDI modules from the power bus.

Magnetic field measurements (Figs. A-22 to A-24) from the composite wing show more of the characteristic spikes from the modules discharging than results from the aluminum wing. This again can be attributed to the shielding effect of the aluminum. These results are difficult to interpret due to the absence of an applicable standard for magnetic field emissions. Even with the composite wing the spikes due not rise significantly above the background level indicating that magnetic field emissions are not a significant problem.

The most interesting and challenging result is the radiated electric field measurements with the composite wing (Figs. A-7 to A-18). Note that the RTCA DO/160B Fig. 21-7 standard is exceeded only in the low frequency band up to 30 MHz. A number of measures were taken to bring the composite wing within emission standards. The first step taken was to enclose the modular power supplies inside of copper shielding (Fig. A-8). This had no beneficial effect, in fact the measured level of emissions appeared to be greater with the shielding. With the failure of this attempt it appeared likely emissions were coming directly off of the LVEIDI coils. The doubler plates supplied with the composite wing borrowed from The Wichita State University were just slightly larger in diameter than the LVEIDI coil. Therefore it seemed likely that the coils could be radiating around the perimeter of the doubler plates. To test this theory copper sheets about 8" square were placed over the doubler plates. Note the dramatic effect on the emission levels in Fig. A-9. Still the RTCA standards are exceeded in a number of places.

Aluminum foil over the composite wing helped to further reduce EMI emissions (see Fig. A-10). Finally wrapping a thin layer of aluminum foil around the wing reduced the emissions to well within standards (Fig. A-11). The importance of broadened doubler plates in addition to the aluminum foil is illustrated in

Fig. A-12. Note that a spike rises above the standard line at 15 MHz. This same result is repeated with little variation in Fig. A-13 with thin .001" aluminum foil inside the composite wing. It appears therefore that without changes in the operation of the LVEIDI module; to bring the system within RTCA DO/160B Fig. 21-7 standards with the composite wing, two measures should be given serious consideration:

1. Doubler plates should be at least twice the diameter of the coil
2. The inside of the wing should be coated with a conducting film or paint

TRANSMISSION LINE RESULTS

The plotted results from test plan items 4-8 are contained in Appendix B. The experiments corresponding Data is recorded on a Gould 4050 100 Msample/sec digital storage oscilloscope (DSO). The scope is triggered by a line run to the LVEIDI module to permit capture of the LVEIDI current pulse and the induced voltages on the cables were captured. Note that the scope probe was connected to only one cable at a time and the input impedance of the scope is 1MΩ 20pF.

Transmission line running through the wing behind the coil

Two 70" cables were run through the Cessna 210 wing section. The cables were run approximately 7 inches behind the de-icing coils and came in direct contact with the energy storage capacitor case. Cable A is an unshielded 6 conductor telephone cable and cable B is RG-58A/U coaxial cable.

The transmission line test results contained in Appendix B are summarized in Tables 7 to 9.

TABLE 7

RESULTS WITH THE TRANSMISSION LINE RUNNING BEHIND THE COIL

Appendix Fig. No.	Description and Results
B-1	One end of the cable was open circuit while the other end is connected to the DSO. This plot shows the induced voltage on the unshielded telephone cable. The peak voltage is -2.17V at 442μsec
B-2	This plot shows the induced voltage on the coaxial cable. The peak voltage is -39.2mV at 508μsec

B-3 The next two tests are the same as above except both ends of the cable are terminated by 50Ω resistors. This first plot is for the unshielded telephone cable.

B-4 Same as above except using the coaxial cable. Note that both tests with 50Ω termination have peak voltage levels below 5mV.

Transmission line running through the wing lashed into contact with the LVEIDI power feed cable

Two 32" cables, A & B, were wrapped 3 times around and lashed to the LVEIDI 240VAC power feed cable. Cable A is an unshielded 6 conductor telephone cable and cable B is RG-58A/U.

TABLE 8

RESULTS WITH THE TRANSMISSION LINE LASHED TO THE LVEIDI POWER FEED CABLE

Appendix Fig. No.	Description and Results
B-5	The plot is dual trace. Trace 1 is the current waveform of the LVEIDI module. Trace 2 is the waveform from the open circuit unshielded cable. The peak induced voltage is 1.66V at 154μsec. The peak LVEIDI current is 2620A at 132usec.
B-6	The plot is dual trace. Trace 1 is the current waveform of the LVEIDI module. Trace 2 is the waveform from a shielded coaxial cable. The peak induced voltage is 32.9mV at 147μsec. The peak LVEIDI current is 2620A at 132usec.
B-7	Same as above except both cables are terminated by 50Ω resistors. Trace 2 shows the result for the unshielded cable and trace 1 shows the result for the coaxial cable. Note that the induced voltage levels are below the noise threshold.

Compass flux valve tests

A compass flux valve was installed at the external tip of the aircraft wing section. An unshielded 4 conductor cable was run down the wing section from the transmitter to the indicating meter. The cables were approximately 7 inches behind the de-icing coils and came in direct contact with the energy storage capacitor case. The "front" of the transmitter was pointed to North.

TABLE 9

COMPASS FLUX VALVE RESULTS

Appendix Fig. No.	Description and Results
B-8	Trace 2 is the LVEIDI current pulse. Trace 1 is the "400 Hz" differential signal on compass connection lines A and B. A 100X probe is employed so the vertical scale should be interpreted as 100V/DIV. Note that the chopper employed by the compass makes a relatively noisy signal. No disturbance of the signal could be detected from firing of the LVEIDI module. In addition, operation of the compass was not noticeably affected by LVEIDI operation.
B-9	Trace 2 is the LVEIDI current pulse. Trace 1 is the "400 Hz" differential signal on compass connection lines C and D. No disturbance of the signal was detected from firing of the LVEIDI module.

CONCLUSIONS

Measurements of the radiated electric field at Eldec indicate that emissions from the aluminum wing were well within the standards set by RTCA/DO-160B Section 21. Some tests with the composite wing were within standards while others were not. Standards were exceeded in the low frequency band of 150 kHz to 30 MHz. Even in this frequency band it was found that the wing could be brought into compliance through the addition of thin metallic shielding.

Conducted emissions on the Low Voltage Electro-Impulse De-icing (LVEIDI) module power feed cable were brought within RTCA/DO-160B Section 21 standards with the addition of an isolating line choke at the bus insertion point. The noise conducted up the power line was apparently due to the use of diodes in the LVEIDI doubler circuit. During application only one filter would be required at the point

where all LVEIDI modules are powered off of the aircraft bus to alleviate this condition.

No problems were observed in tests on the wing internal environment. A 2.2 volt signature was measured on an open circuit unshielded telephone wire run behind the deicing module. The EMI signal was a voltage spike which occurs simultaneous with discharge of the coil. A 2.2 volt spike would be adequate to create an error on a digital transmission line. But this signal was reduced to insignificant levels by terminating the cable with 50 ohms, the usual termination for digital information transfer. The addition of shielding also reduced the signal to an insignificant level. An unshielded connection cable for a compass flux valve was run through the wing just behind the LVEIDI module. Discharge of the LVEIDI module had no discernible effect on operation of the compass flux valve.

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APPENDIX A

DATA FROM RADIATED AND CONDUCTED ELECTROMAGNETIC EMISSIONS TESTS PERFORMED IN THE ELDEC EMI LABORATORY

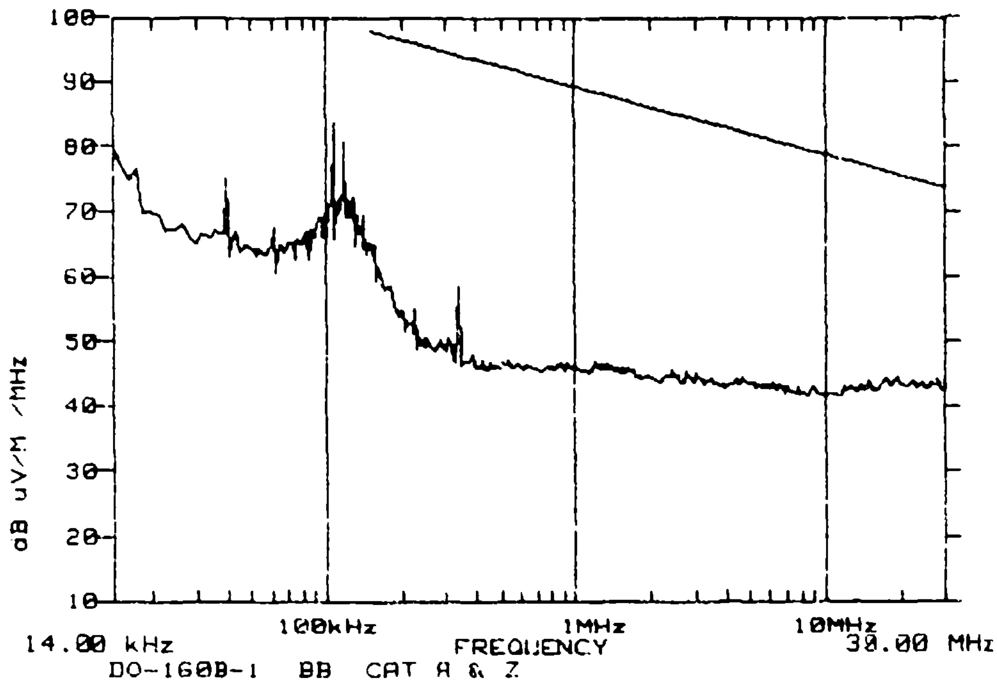

Figure A-1 Electric field emissions from the aluminum wing in a vertical orientation as per DO160B. The frequency range is 14 kHz to 30 MHz. Emission levels are within standards.

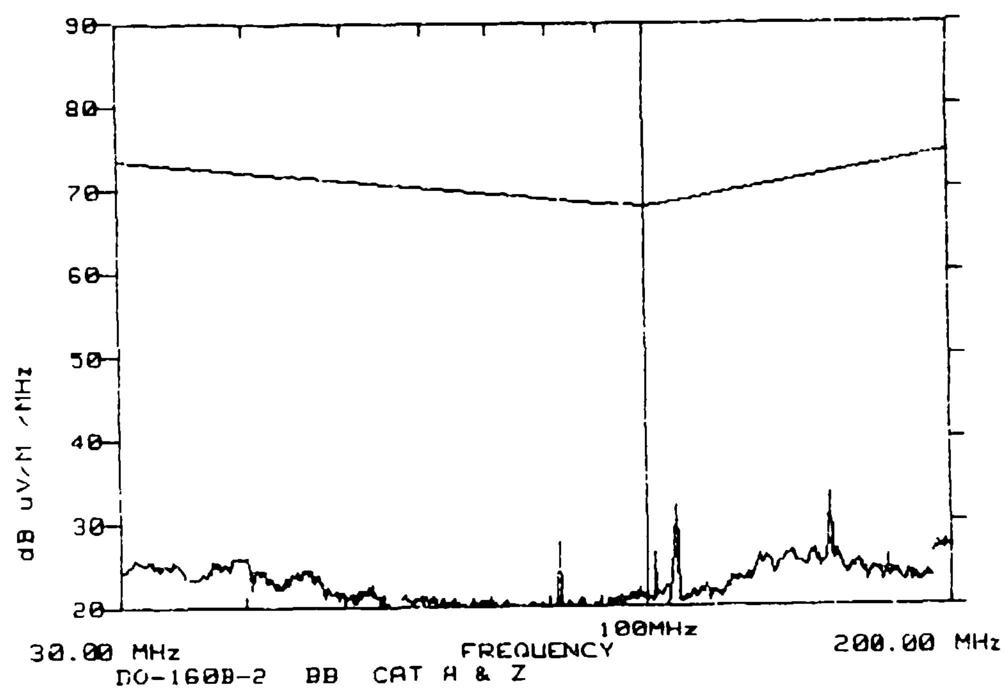

Figure A-2 Electric field emissions from the aluminum wing in a vertical orientation as per DO160B. The frequency range is 30 MHz to 200 MHz. Emission levels are within standards.

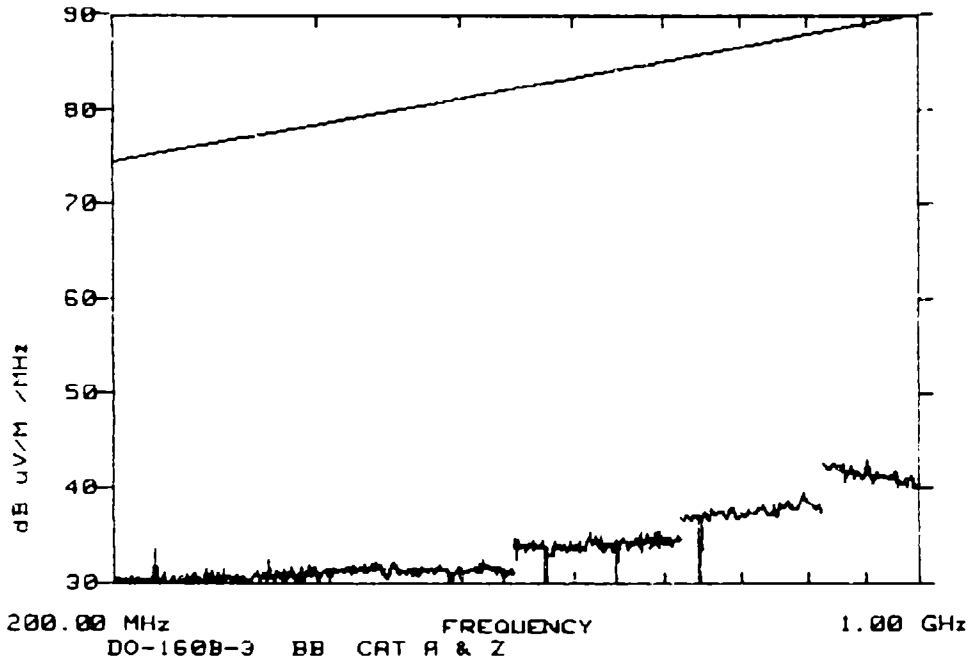

Figure A-3 Electric field emissions from the aluminum wing in a vertical orientation as per DO160B. The frequency range is 200 MHz to 1 GHz. Emission levels are within standards.

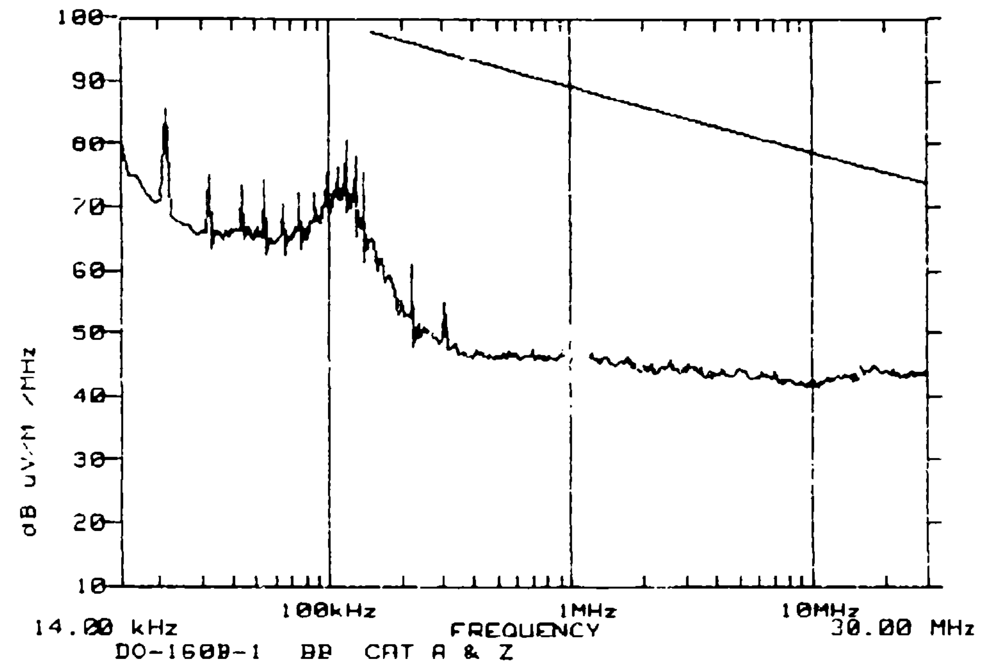

Figure A-4 Electric field emissions from the aluminum wing in a horizontal orientation as per DO160B. The frequency range is 14 kHz to 30 MHz. Emission levels are within standards.

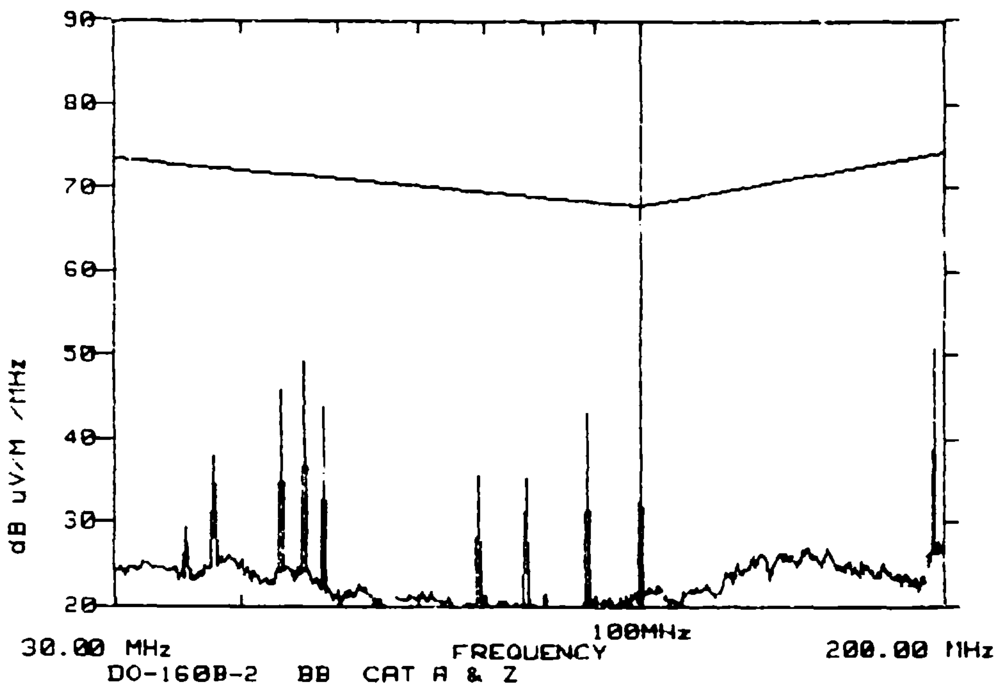

Figure A-5 Electric field emissions from the aluminum wing in a horizontal orientation as per DO160B. The frequency range is 30 MHz to 200 MHz. Emission levels are within standards.

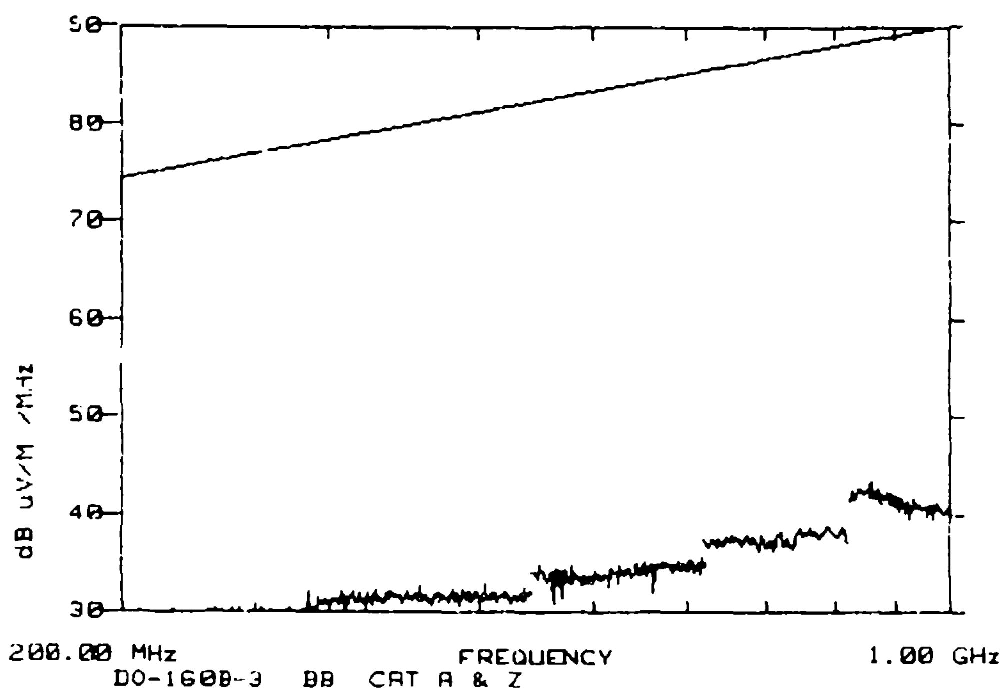

Figure A-6 Electric field emissions from the aluminum wing in a horizontal orientation as per DO160B. The frequency range is 200 MHz to 1 GHz. Emission levels are within standards.

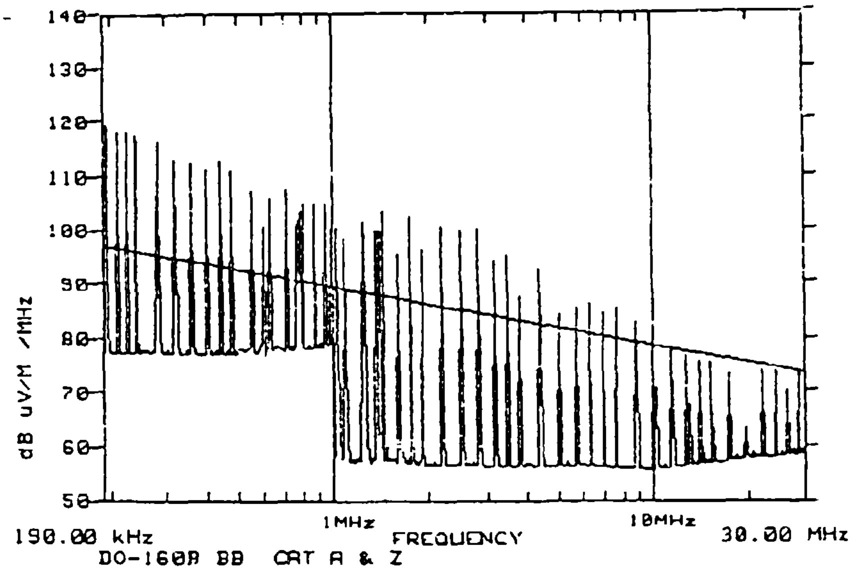

Figure A-7 Electric field emissions from the composite wing in a vertical orientation as per DO160B. The frequency range is 190 kHz to 30 MHz. Emission levels exceed standards.

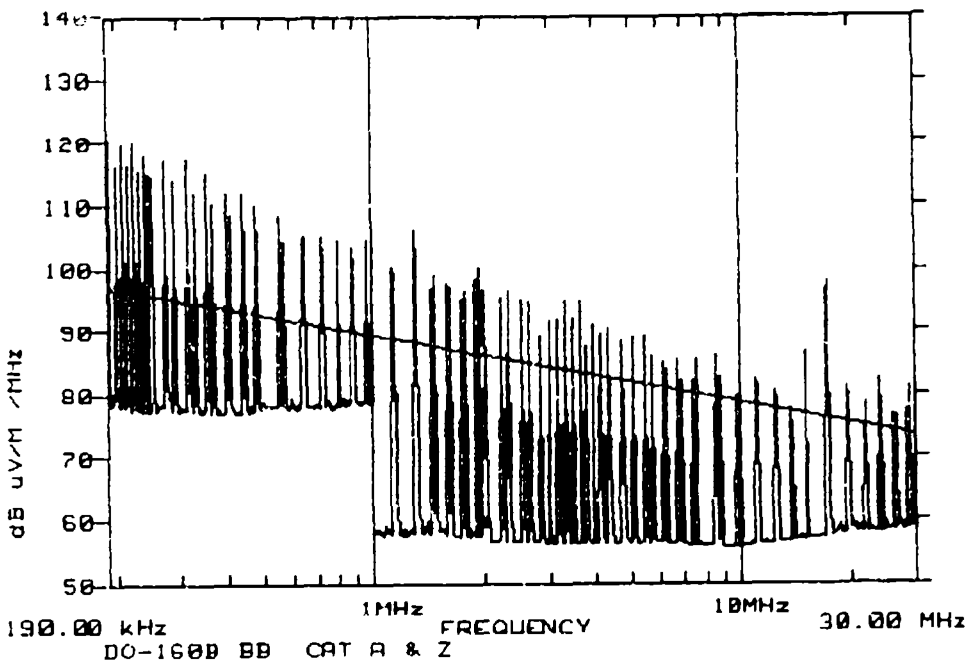

Figure A-8 Electric field emissions from the composite wing in a vertical orientation as per DO160B. The frequency range is 190 kHz to 30 MHz. Shielding has been placed over the power supplies. Emission levels exceed standards.

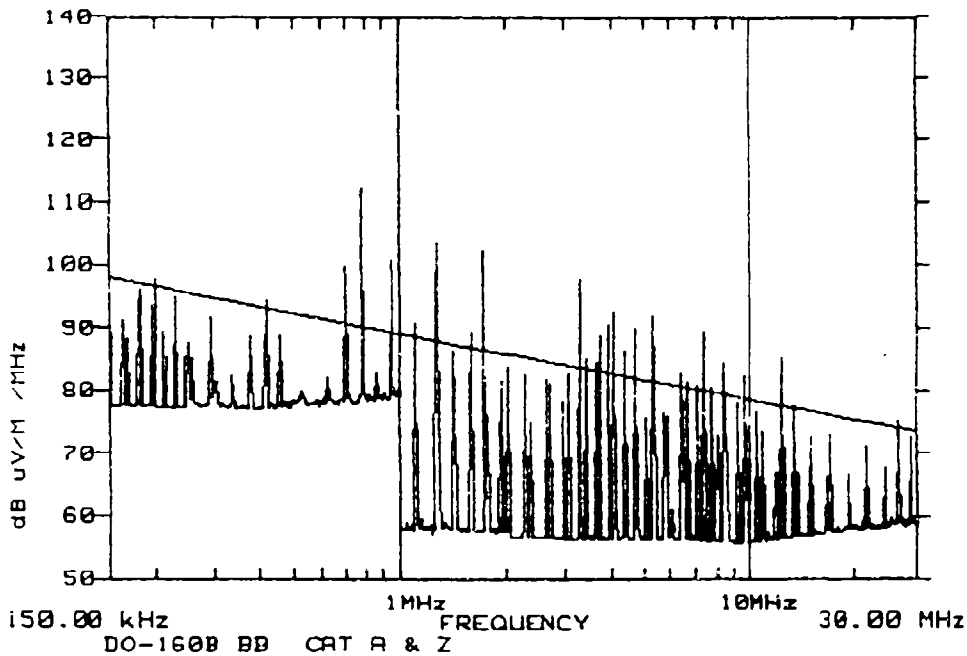

Figure A-9 Electric field emissions from the composite wing in a vertical orientation as per DO160B. The frequency range is 150 kHz to 30 MHz. Shielding has been placed over the power supplies and the doubler plates have been broadened with copper sheets. The standard is exceeded.

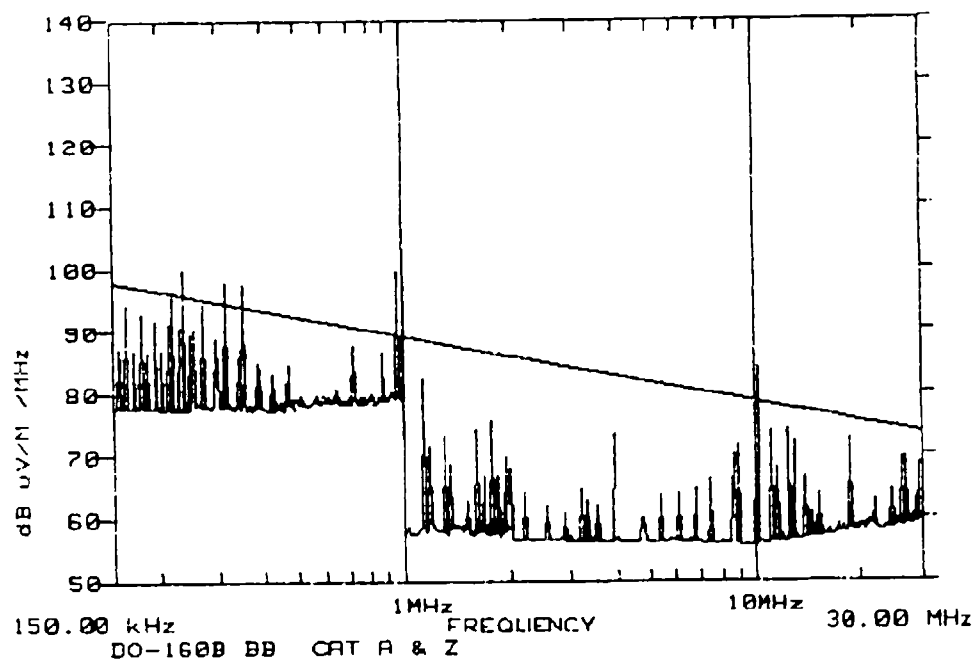

Figure A-10 Electric field emissions from the composite wing in a vertical orientation. The frequency range is 150 kHz to 30 MHz. Shielding is on the power supplies. Doubler plates broadened with copper sheets. The surface is covered with .0013 aluminum foil. The standard is exceeded at several points.

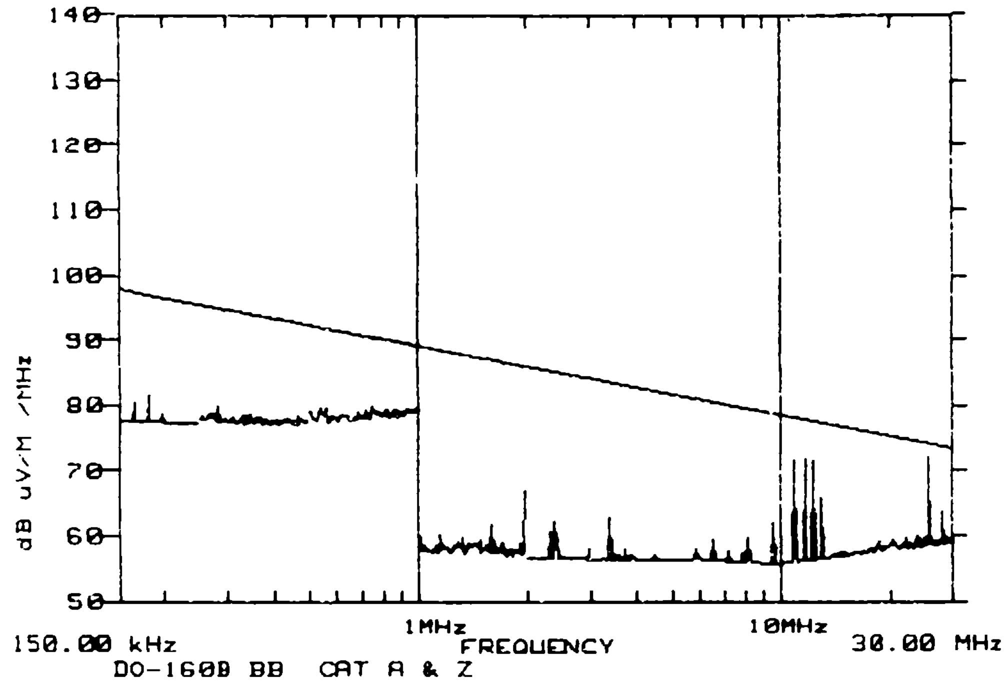

Figure A-11 Electric field emissions from the composite wing in a vertical orientation. The frequency range is 150 kHz to 30 MHz. Shieldsplaced over the power supplies. The doubler plates broadened with copper sheets. The wing covered with .0013 aluminum foil. Emissions levels are within standards.

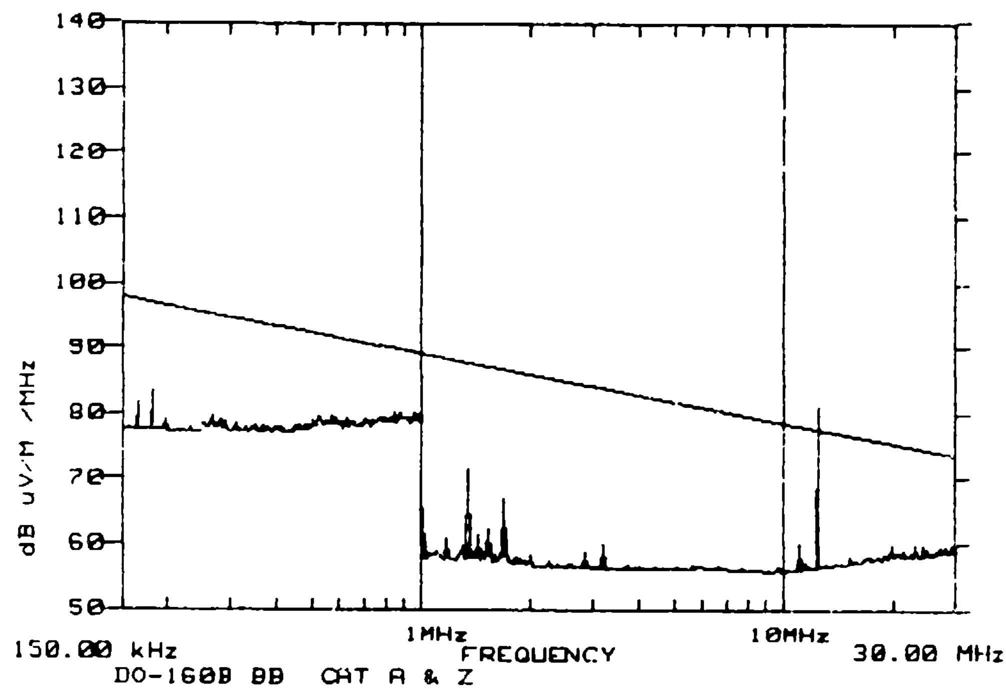

Figure A-12 Electric field emissions from the composite wing in a vertical orientation. The frequency range is 150 kHz to 30 MHz. Shields placed over the power supplies. The broadened doubler plates removed. The wing covered with .0013 aluminum foil. There is one spike above the emission limit line.

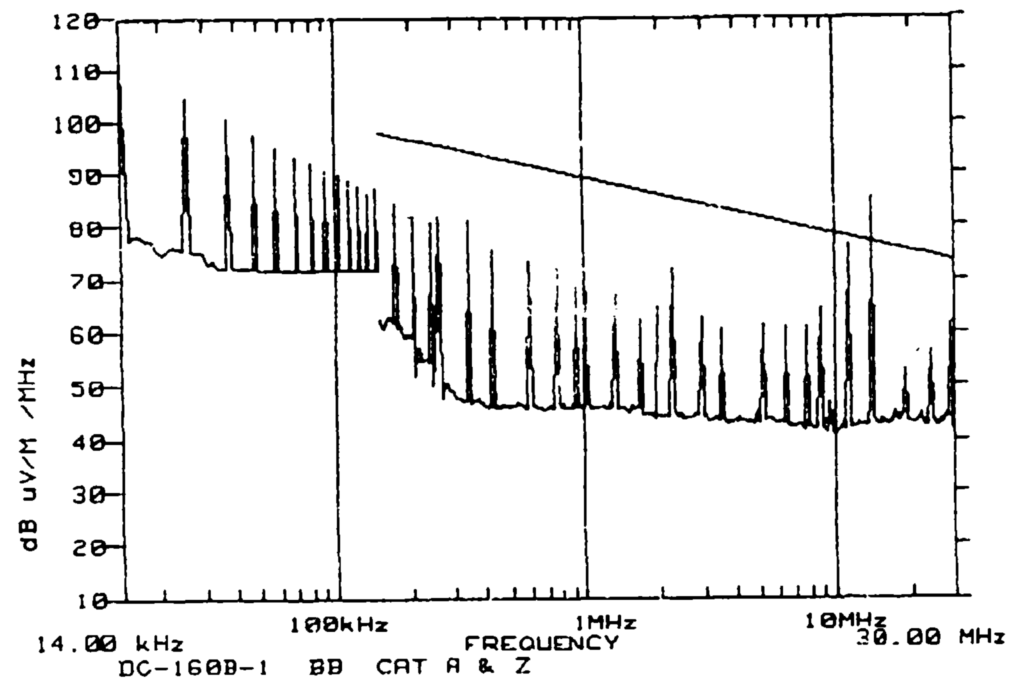

Figure A-13 Electric field emissions from the composite wing in a vertical orientation as per DO160B. The frequency range is 150 kHz to 30 MHz. Shields placed over the power supplies. The wing is internally covered with .001 aluminum foil. There is one spike above the emission limit line near 15 MHz.

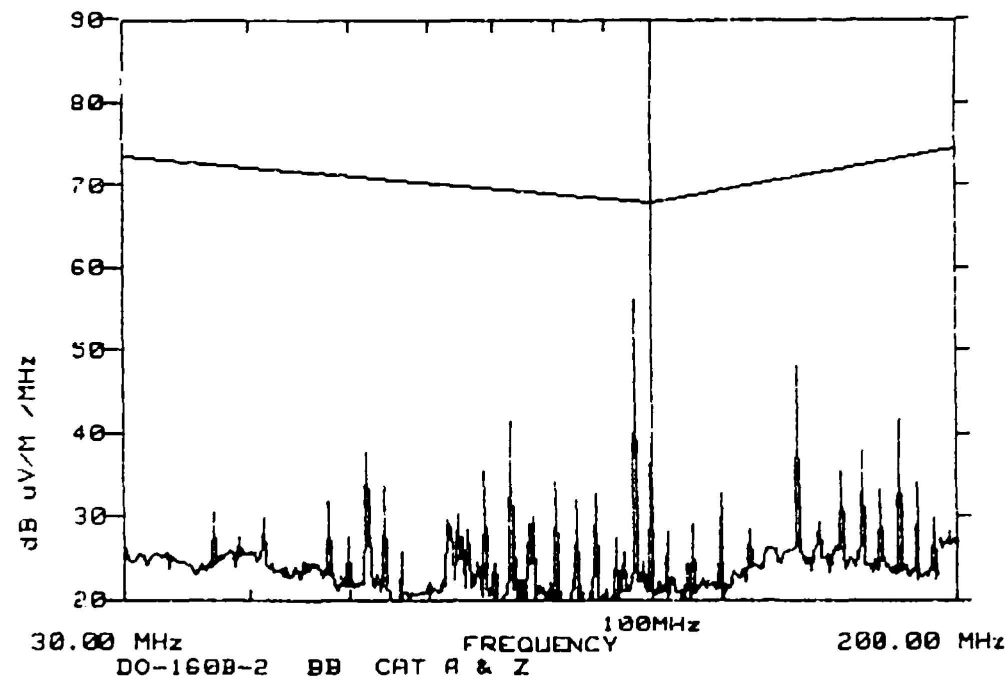

Figure A-14 Electric field emissions from the composite wing in a vertical orientation as per DO160B. The frequency range is 30 MHz to 200 MHz. Emission levels are within standards.

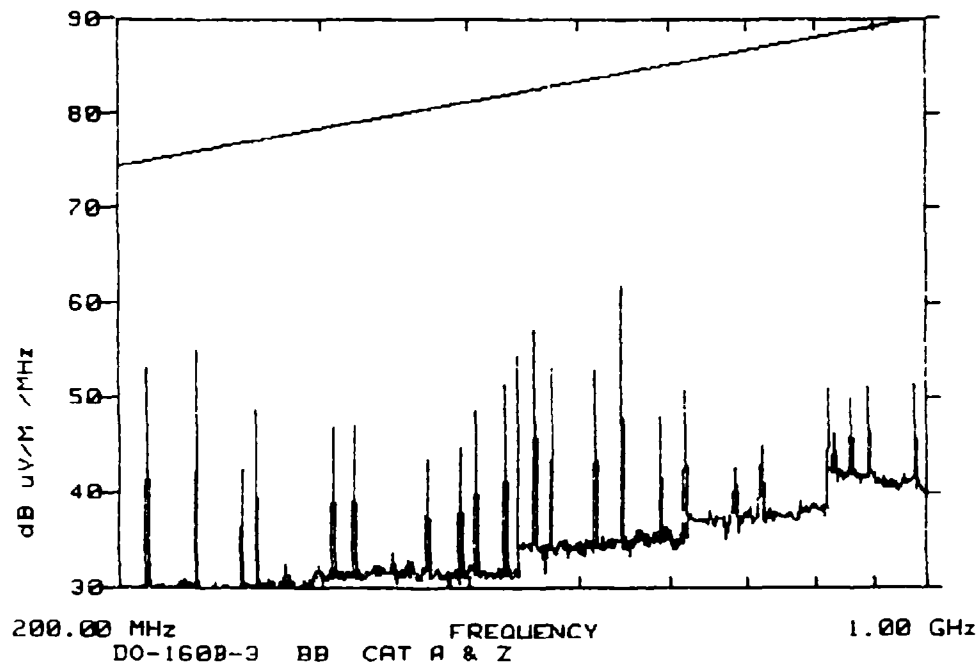

Figure A-15 Electric field emissions from the composite wing in a vertical orientation as per DO160B. The frequency range is 200 MHz to 1 GHz. Emission levels are within standards.

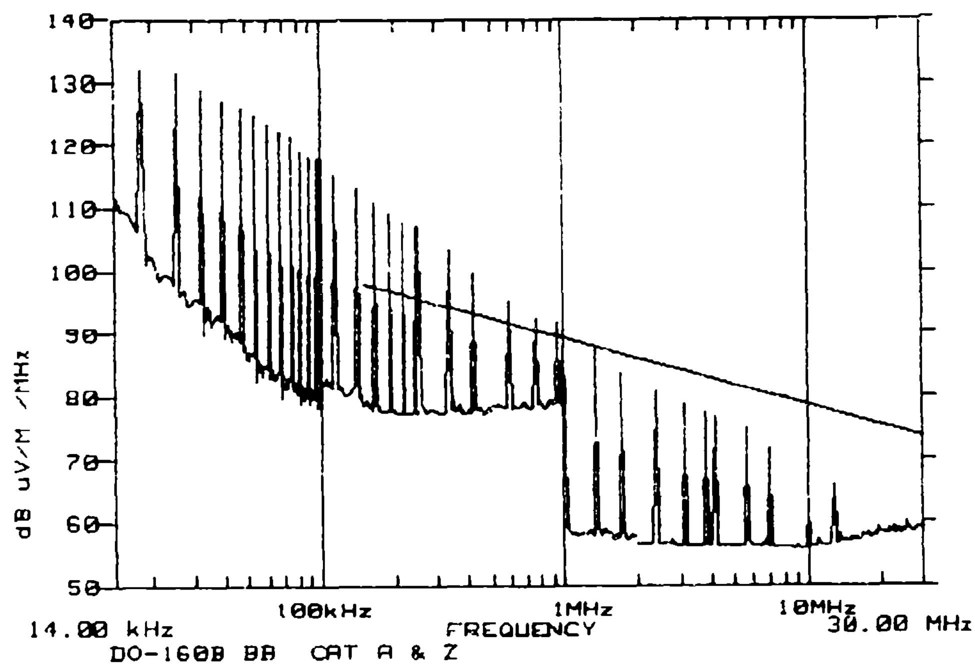

Figure A-16 Electric field emissions from the composite wing in a horizontal orientation as per DO160B. The frequency range is 14 kHz to 30 MHz. Emission levels exceed standards.

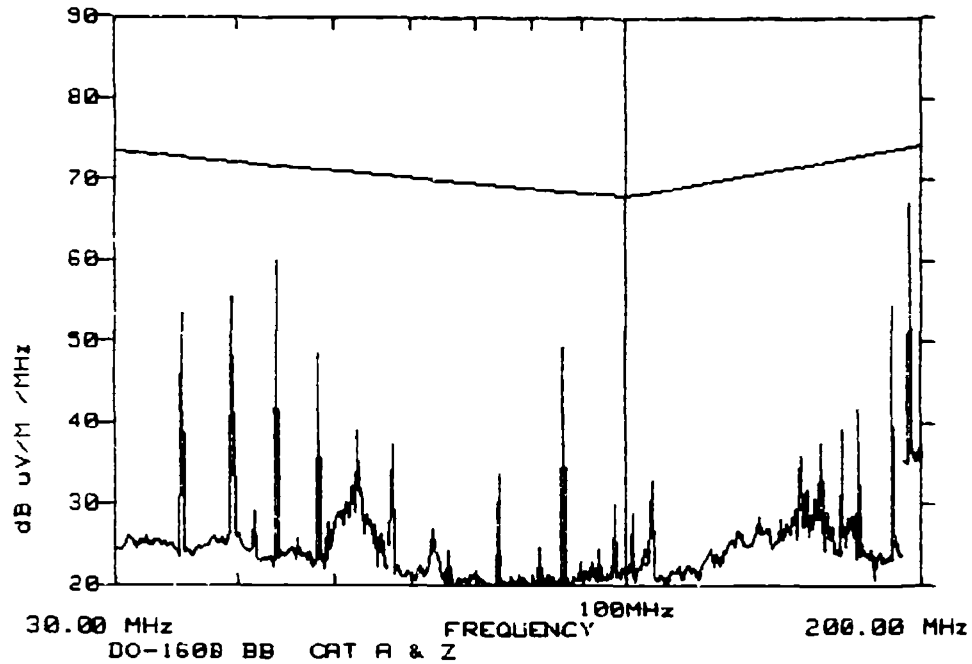

Figure A-17 Electric field emissions from the composite wing in a horizontal orientation as per DO160B. The frequency range is 30 MHz to 200 MHz. Emission levels are within standards.

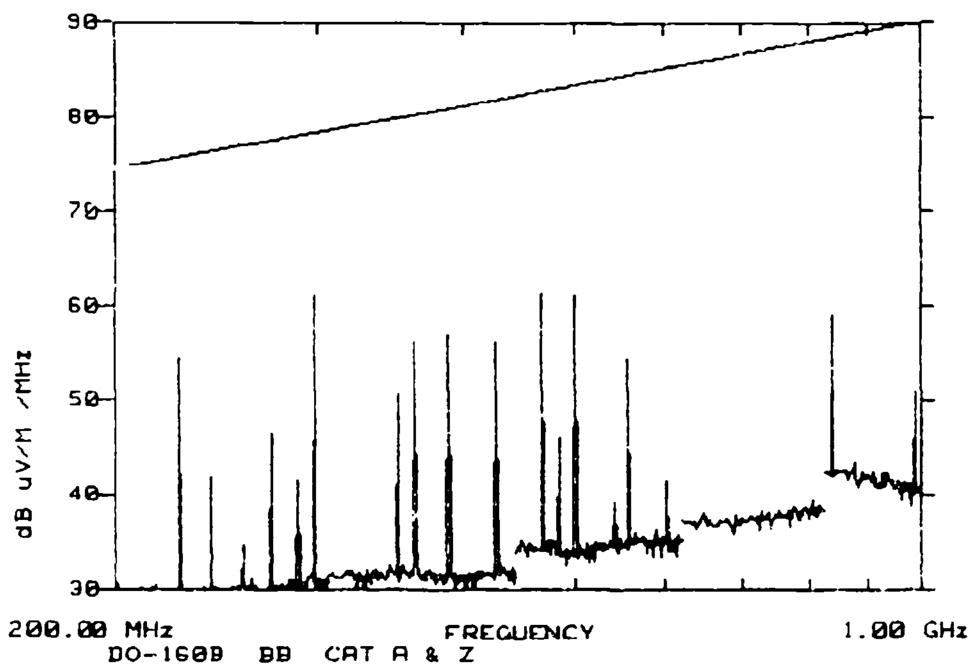

Figure A-18 Electric field emissions from the composite wing in a horizontal orientation as per DC160B. The frequency range is 200 MHz to 1 GHz. Emission levels are within standards.

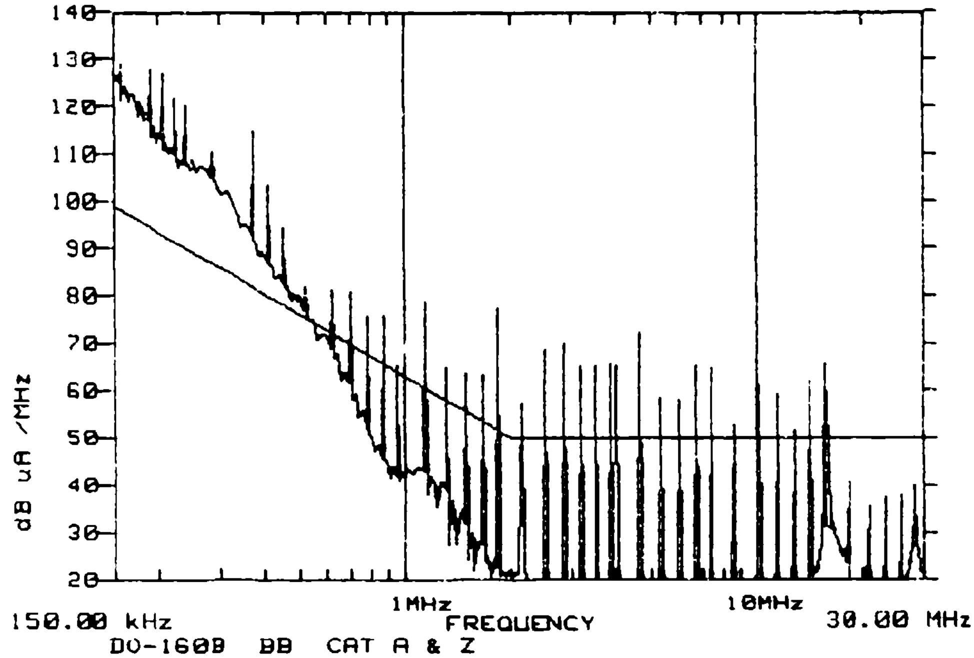

Figure A-19 Conducted interference measurement on the power feed cable as per DO160B in the frequency range of 150 kHz to 30 MHz. There is no input filter. The emission limitations are exceeded up to 600 kHz.

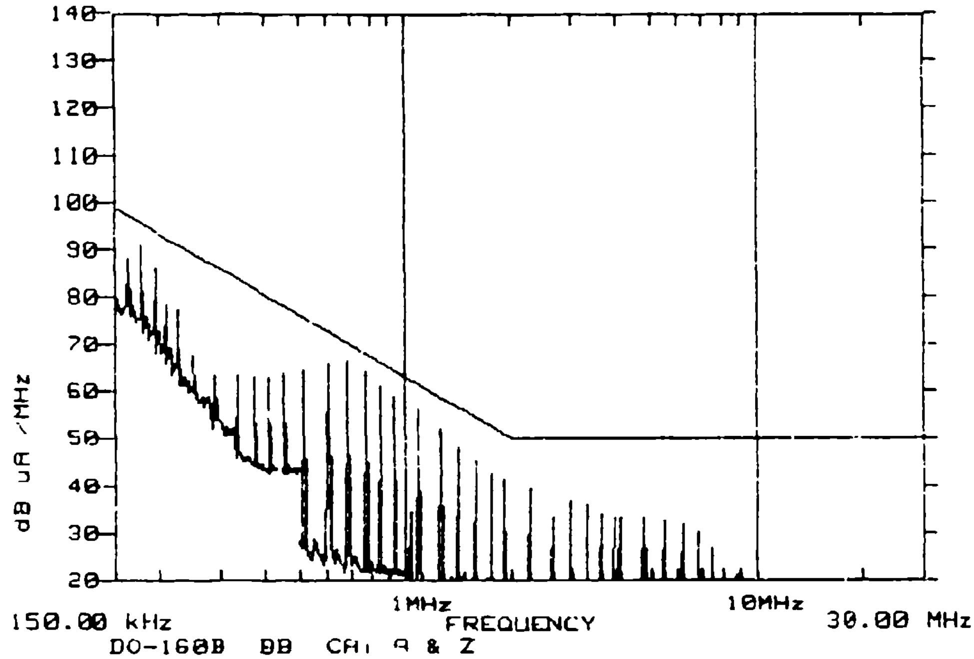

Figure A-20 Conducted interference measurement on the phase A power feed cable as per DO160B in the frequency range of 150 kHz to 30 MHz. A low pass input filter has been added. Emission levels are within standards.

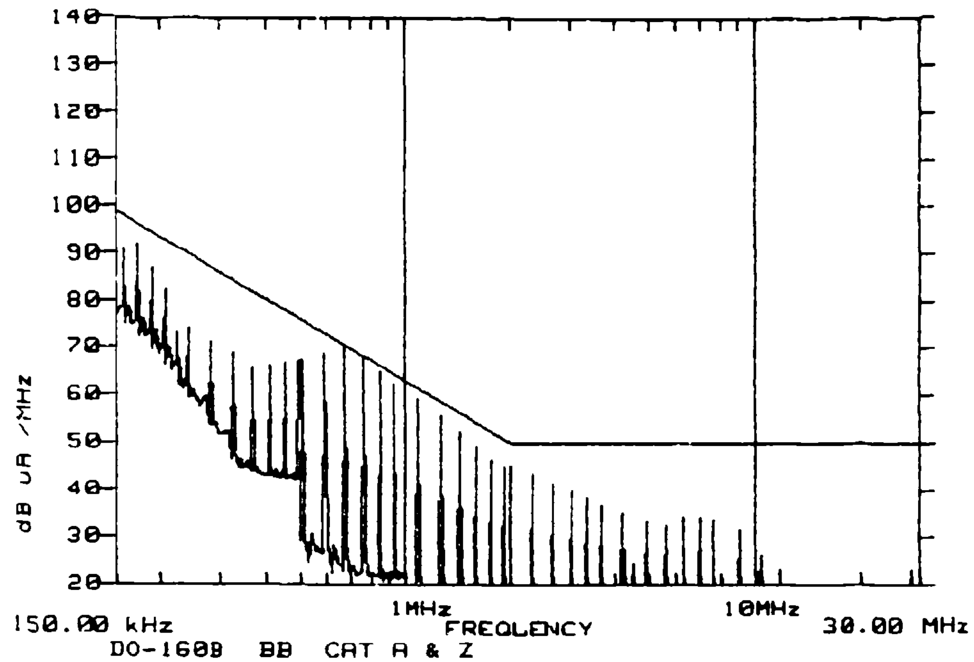

Figure A-21 Conducted interference measurement on the ph~se B power feed cable as per DO160B in the frequency range of 150 kHz to 30 MHz. A low pass input filter has been added. Emission levels are within standards.

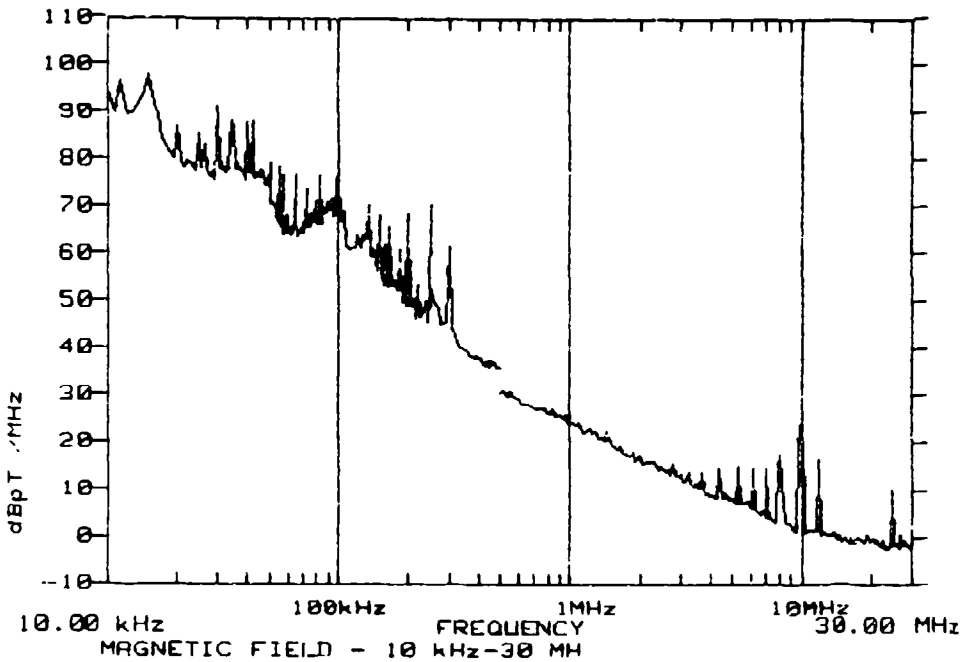

Figure A-22 Magnetic field emissions from the aluminum wing in the frequency range of 10 kHz to 30 MHz. The wing is vertical.

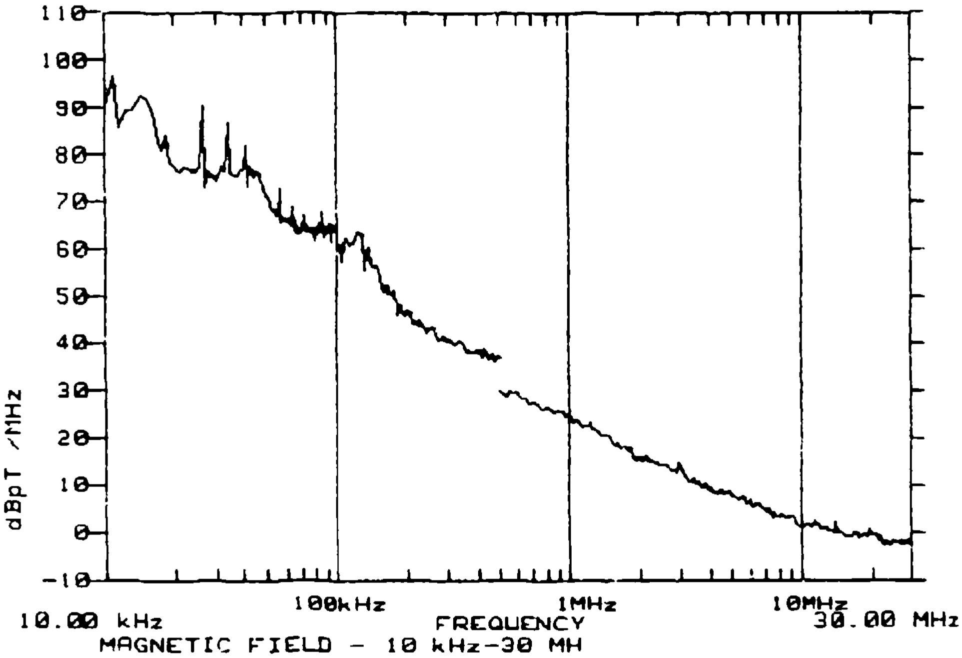

Figure A-23 Magnetic field emissions from the aluminum wing in the frequency range of 10 kHz to 30 MHz. The wing is horizontal.

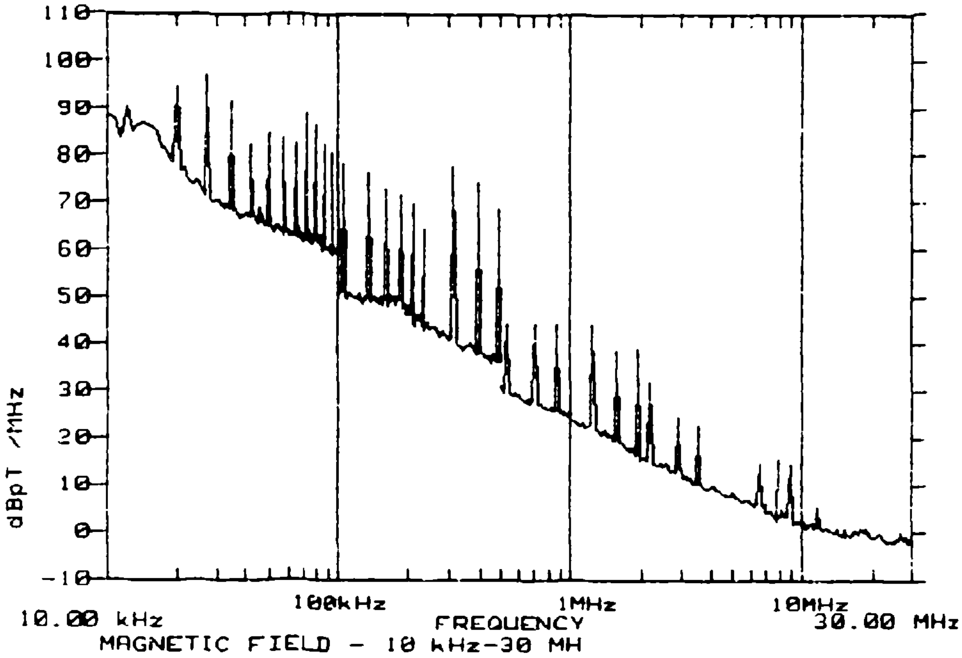

Figure A-24 Magnetic field emissions from the composite wing in the frequency range of 10 kHz to 30 MHz. The wing is vertical.

APPENDIX B

DATA FORM TRANSMISSION LINE EXPERIMENTS PERFORMED IN THE ELECTROIMPACT LABORATORY

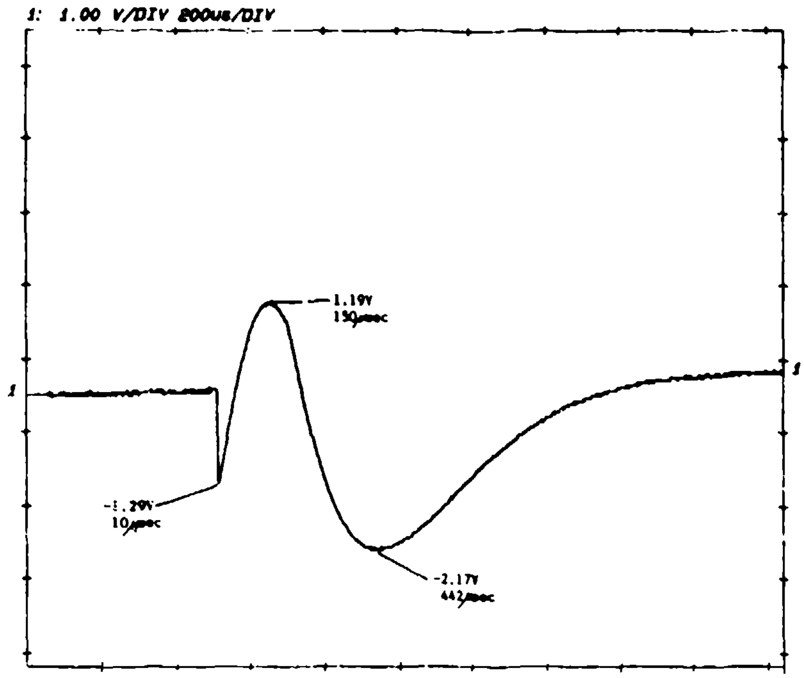

Figure B-1 Trace of induced voltage on an unshielded telephone cable run behind the module. When the module discharges the peak induced voltage is -2.17V at 442µsec from the trigger point.

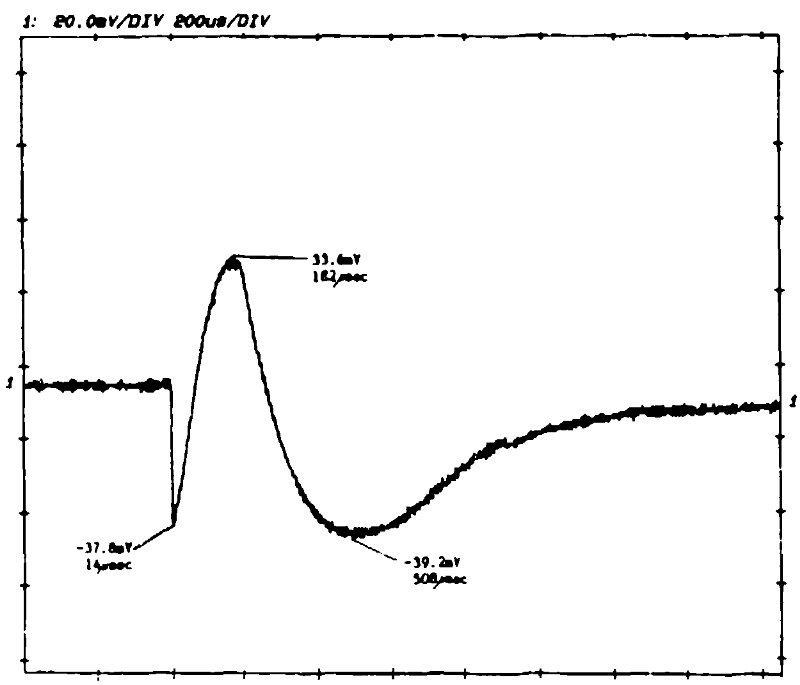

Figure B-2 Trace of induced voltage on a coaxial cable run behind the module. When the module discharges the peak induced voltage is -39.2mV at 508µsec from the trigger point.

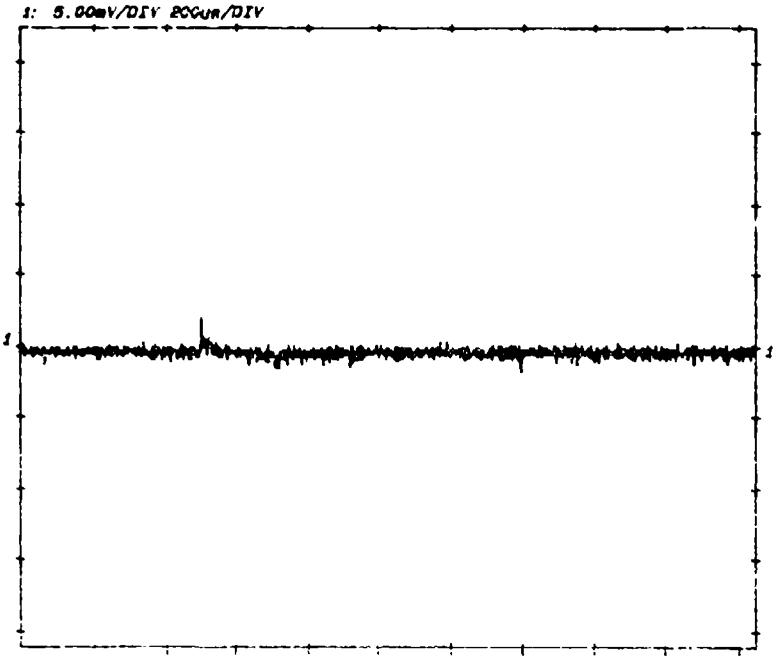

Figure B-3 Trace of induced voltage on an unshielded telephone cable run behind the module with both ends terminated by 50Ω resistors. The induced voltage is below 5mV.

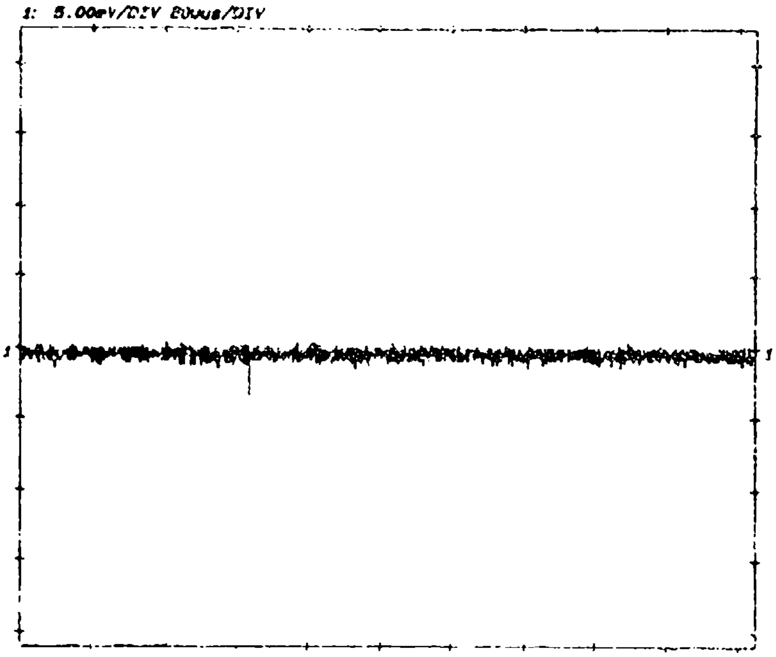

Figure B-4 Trace of induced voltage on a coaxial cable run behind the module with both ends terminated by 50Ω resistors. The induced voltage is below 5mV.

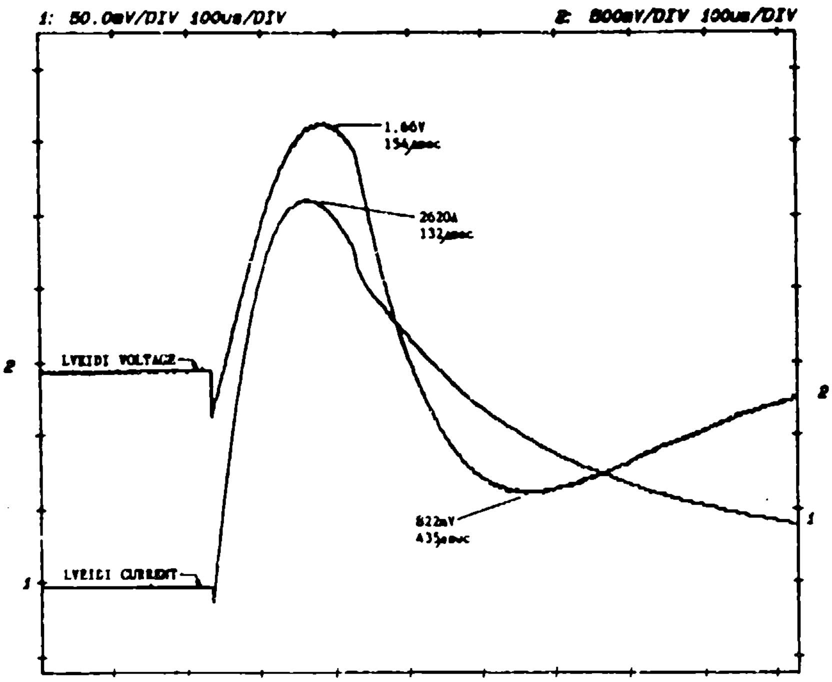

Figure B-5 Trace 1 is the current waveform of the LVEIDI module. The peak current is 2620 A at 132 μsec from the trigger point. Trace 2 is the voltage waveform on an open circuit unshielded telephone cable wrapped around the LVEIDI power feed cable. The peak induced voltage is 1.66V at 154μsec.

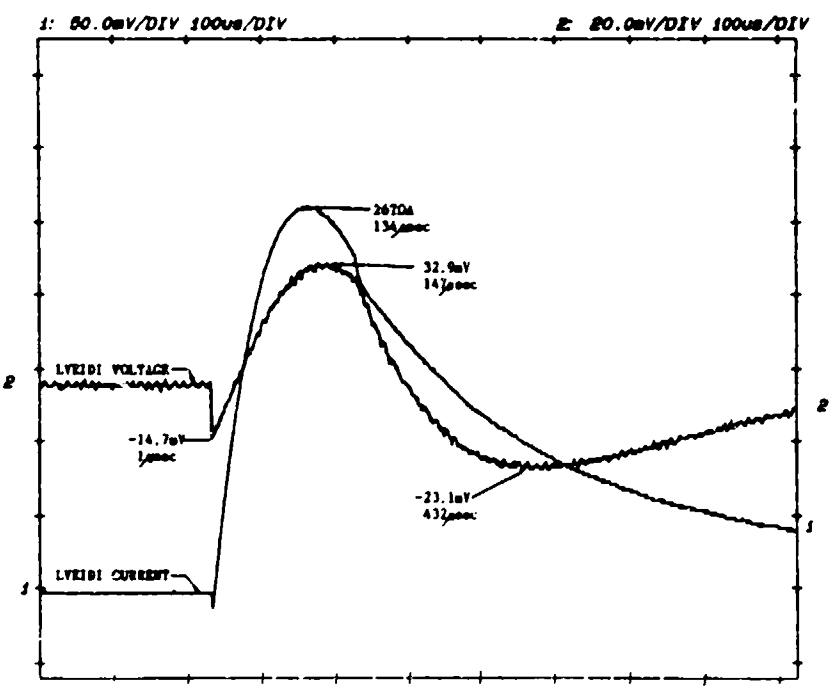

Figure B-6 Trace 1 is the current waveform of the LVEIDI module. The peak current is 2620 A at 134 μsec from the trigger point. Trace 2 is the voltage waveform on a shielded coaxial cable wrapped around the LVEIDI power feed cable. The peak induced voltage is 32.9mV at 147μsec.

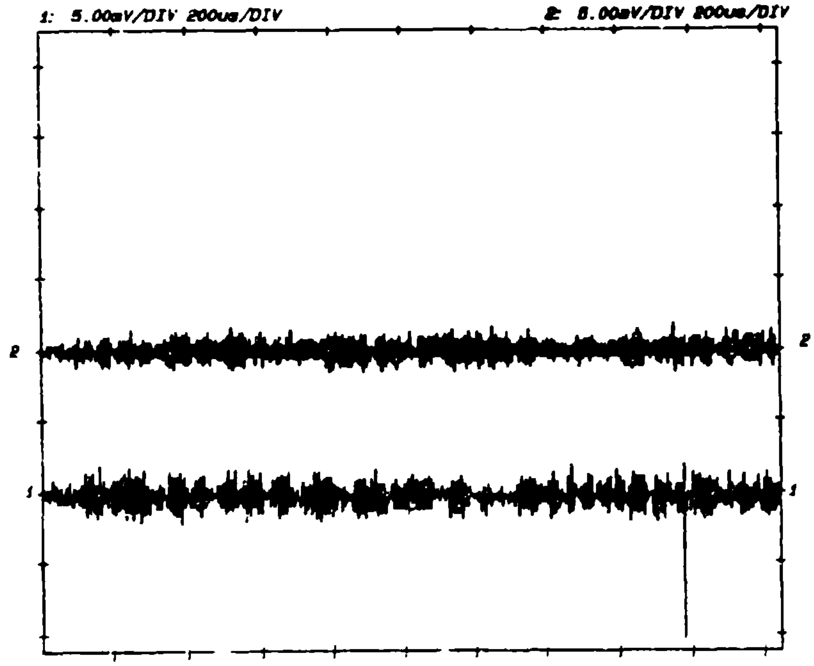

Figure B-7 Trace 1 is the induced voltage on a shielded coaxial cable terminated into a 50Ω resistor. Trace 2 is the induced voltage waveform for the telephone cable terminated into 50Ω. Both cables are terminated by 50Ω resistors. The induced voltage levels for both traces are below the noise threshold.

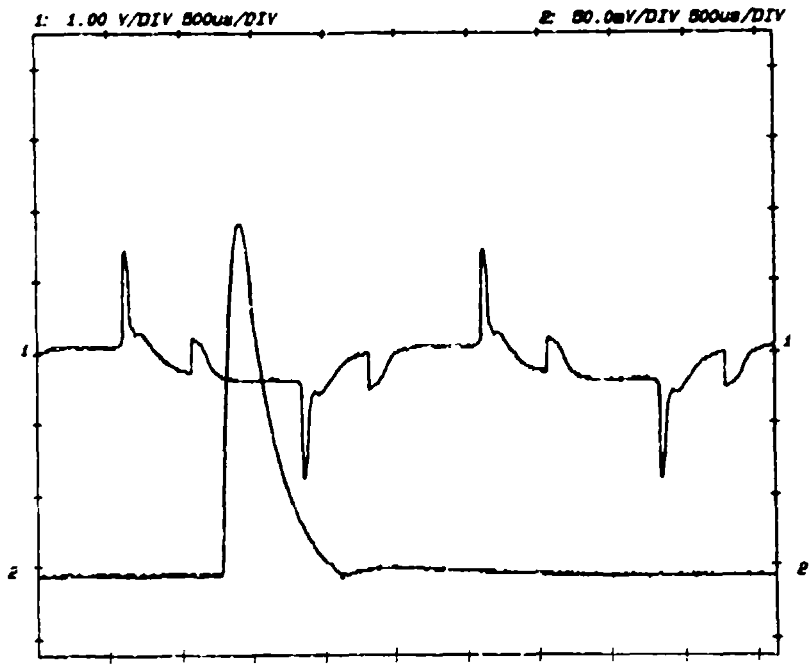

Figure B-8 The connection cable for a compass flux valve is run behind the LVEIDI module. Trace 2 is the LVEIDI current pulse. Trace 1 is the "400 Hz" differential signal on compass connection lines A and B. A 100X probe is employed so the vertical scale should be interpreted as 100V/DIV.

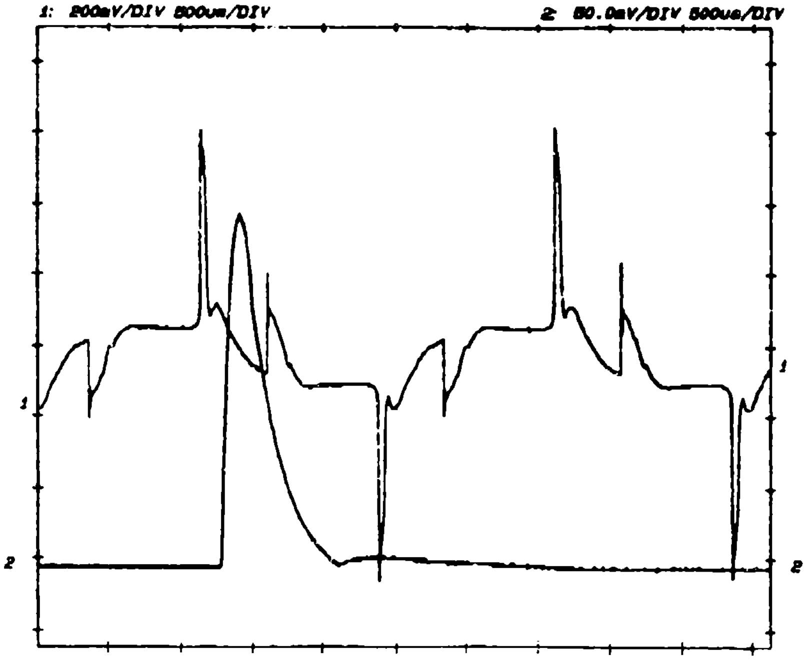

Figure B-9 The connection cable for a compass flux valve is run behind the LVEIDI module. Trace 2 is the LVEIDI current pulse. Trace 1 is the "400 Hz" differential signal on compass connection lines C and D. A 100X probe is employed so the vertical scale should be interpreted as 100V/DIV.